Flavour physics.

Terascale Summer School 2020

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11.08.2020

Goals for this lecture

0) What is flavour and “flavour physics”.

1) Understand the basics and motivations of flavour physics
   - Enough to talk to us even if you don’t end up working in our field.
   - Know the names and rough idea behind four of the important b-physics experiments.
   - Know enough to “get the gist” of a flavour physics paper.

2) Know a bit about “recent anomalies” and their implications
   - Real cutting-edge physics results.

What is the Standard Model?

Precision of statement

An effective relativistic quantum field theory gauge invariant under
SU(3) . SU(2) . U(1).

A Lagrangian density which is the closest we've come to finding the Lagrangian density of nature.

A collection of quantum fields and their couplings.

A collection of quantum fields and their interactions.

A collection of different types of squiggly lines and rules to draw them.

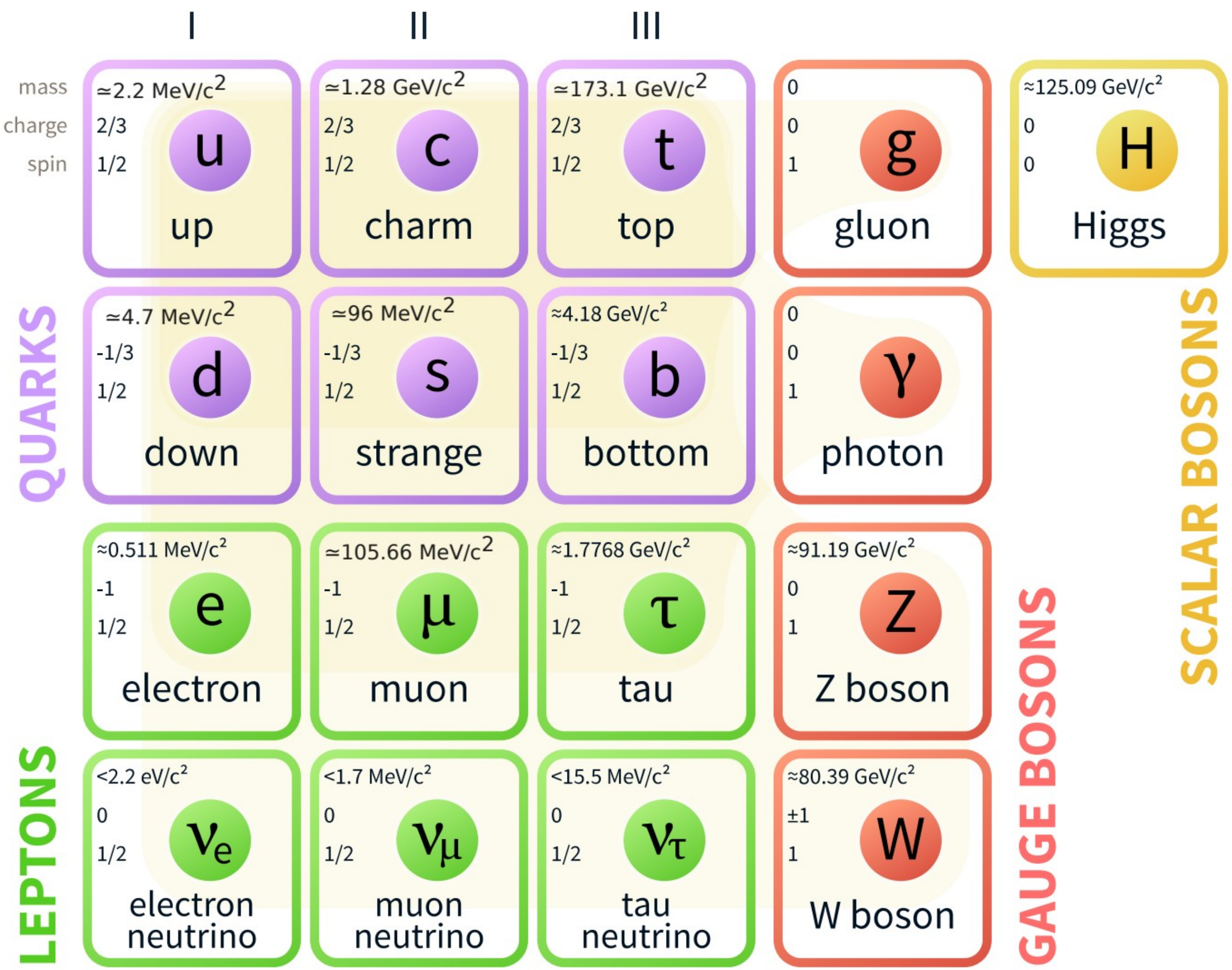
A framework for theorists to calculate predictions of measurable quantities

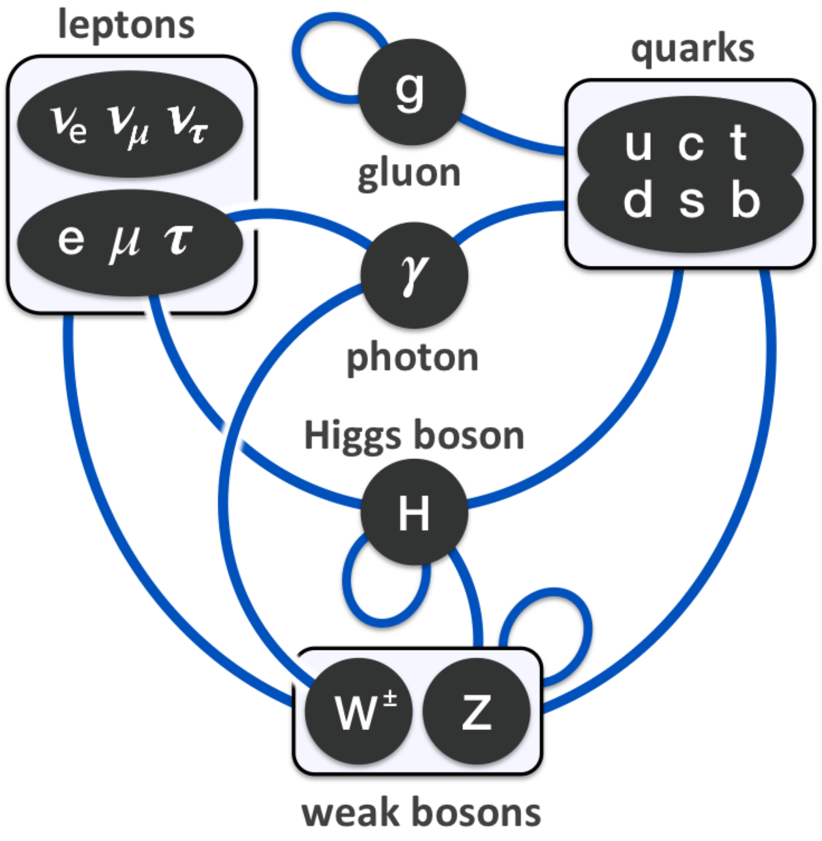
A table of particles on wikipedia.

A set of rules for really small and really fast things.

Amount of QFT lectures necessary

What is the Standard Model?





Figures: MissMJ, Eric Drexler /Wikimedia Commons

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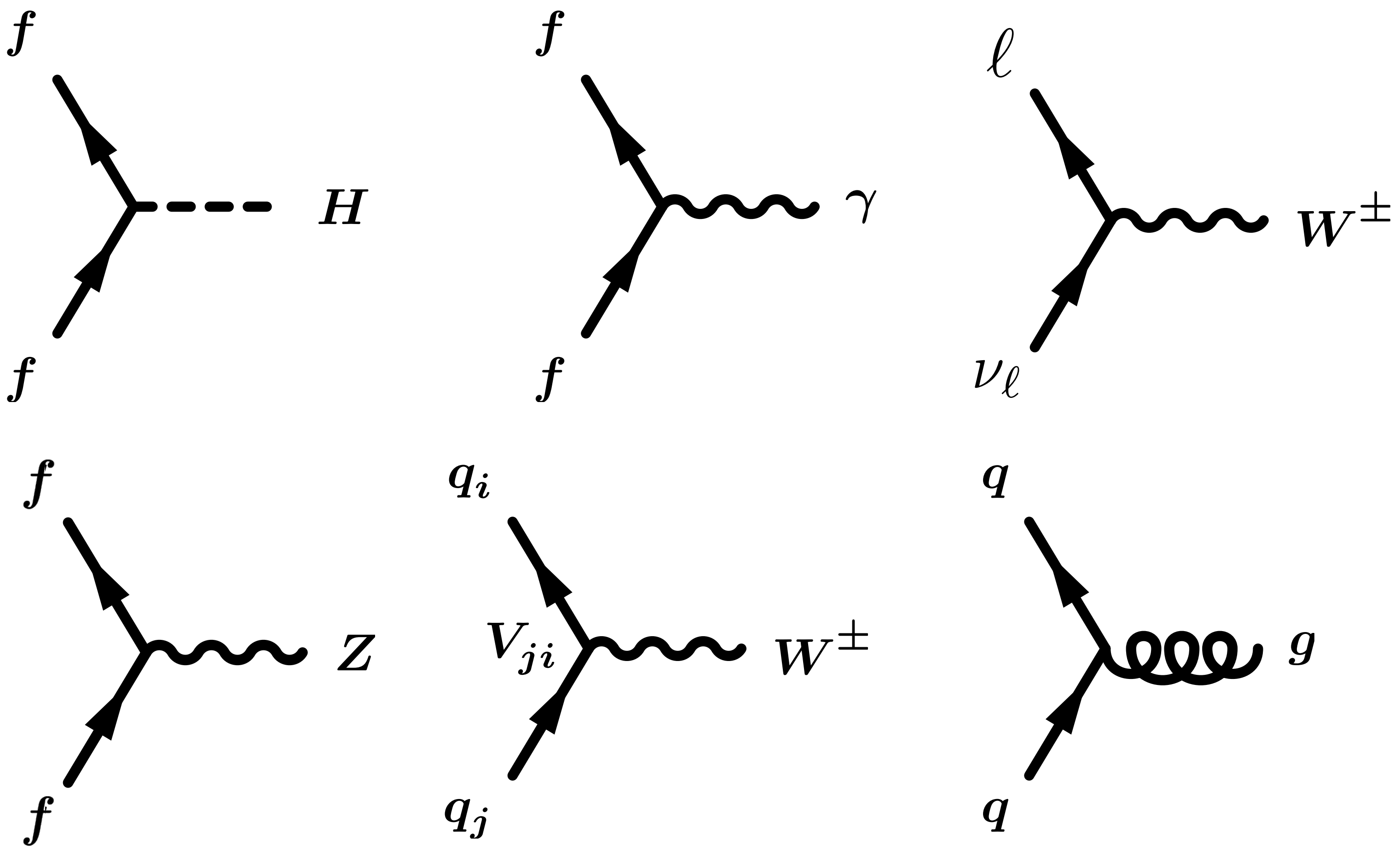


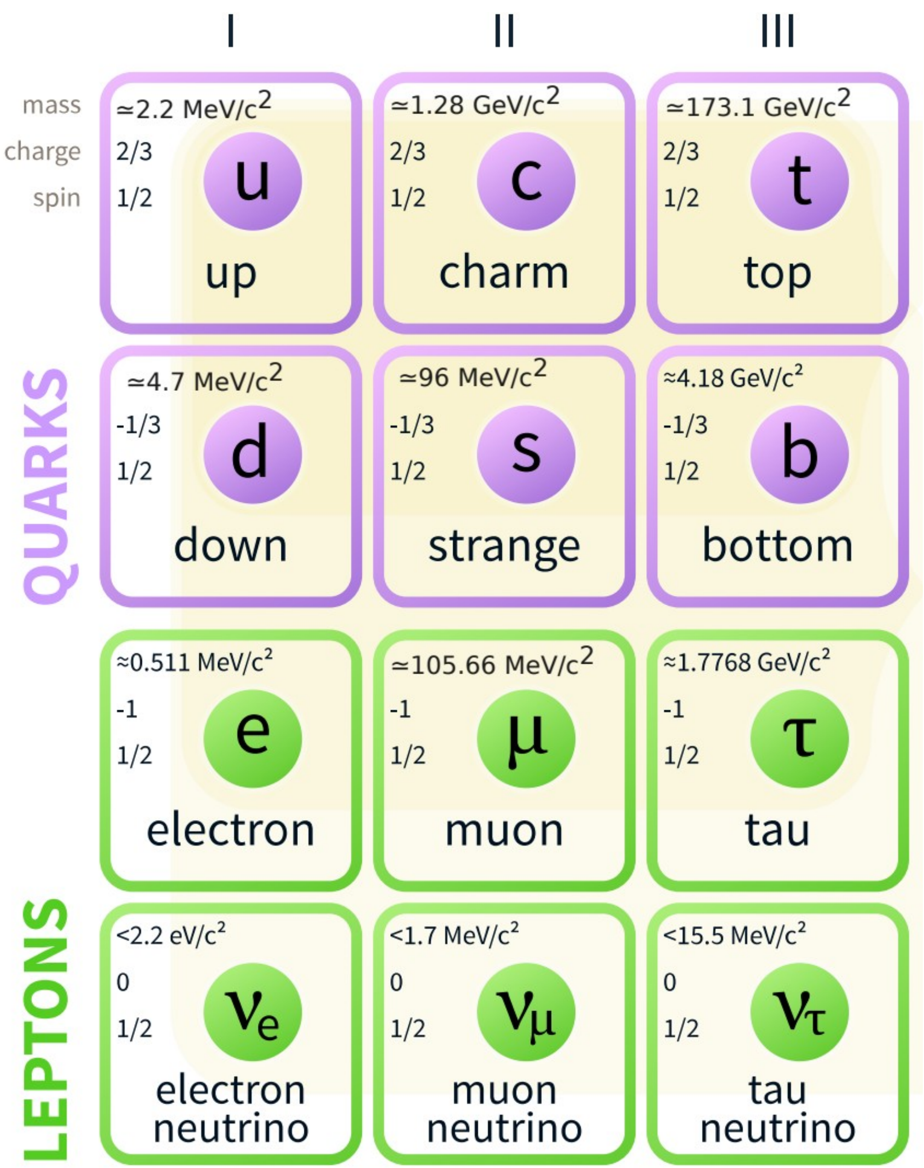
$f =$ Fermion (q or ℓ)

$\ell =$ Charged lepton

$q =$ (Any) quark

$q_i =$ A specific quark

What is flavour?

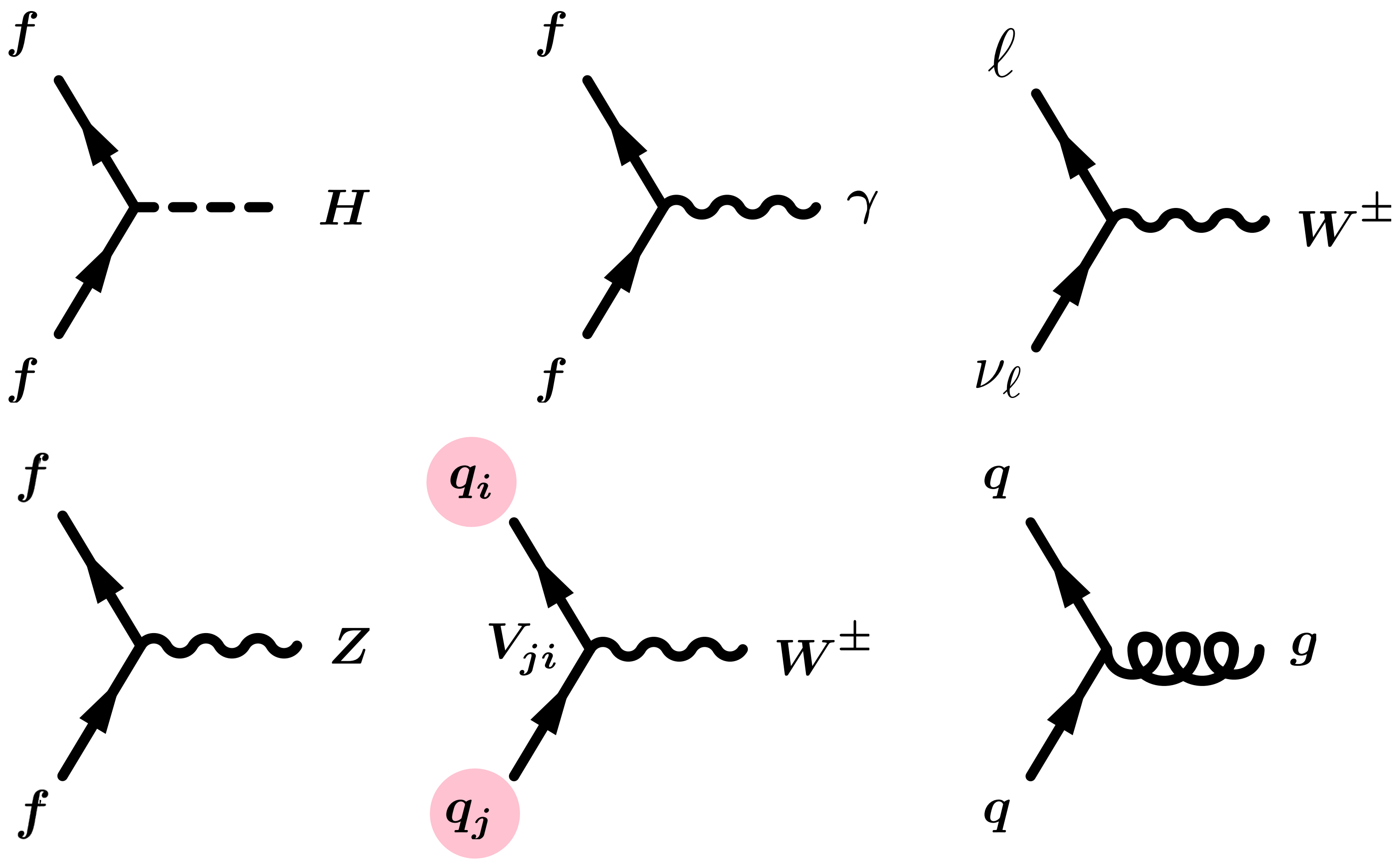


Depends a bit on nomenclature, *but*:

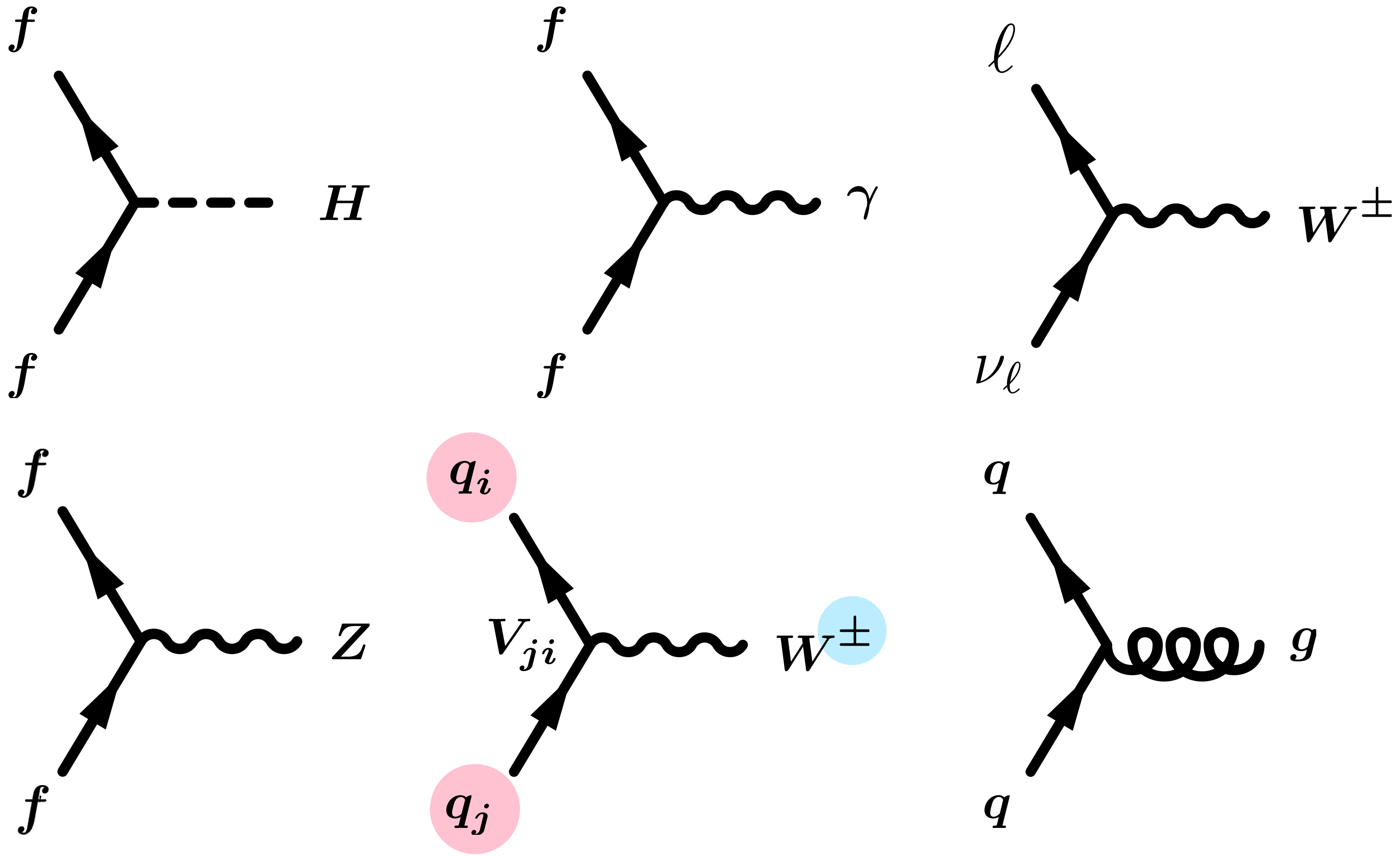
- **Columns**: families / generations
- **Rows**: type
- **Cells**: flavour

What is flavour?

The symbol you substitute into these for f, q or ℓ



How to change flavour?



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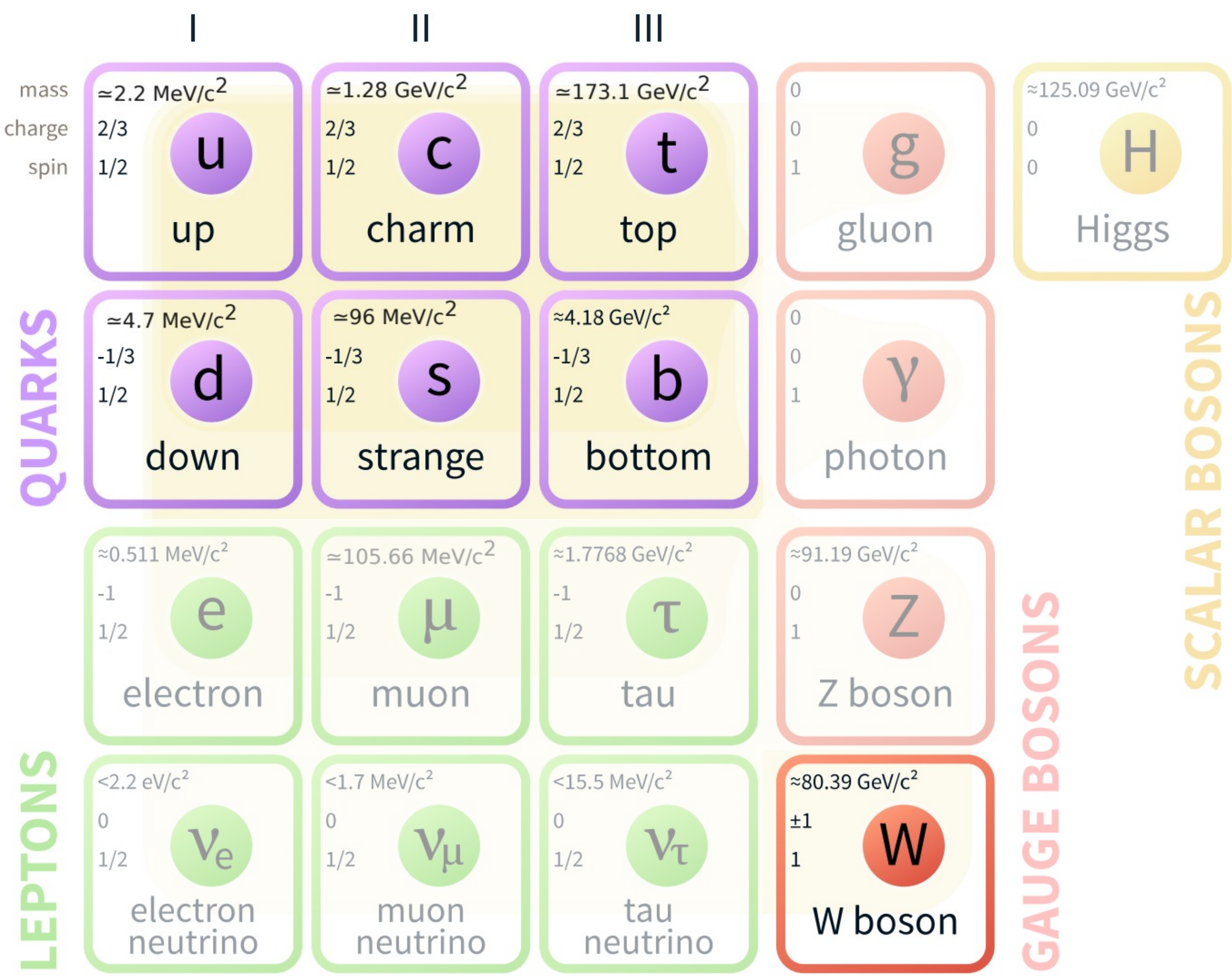
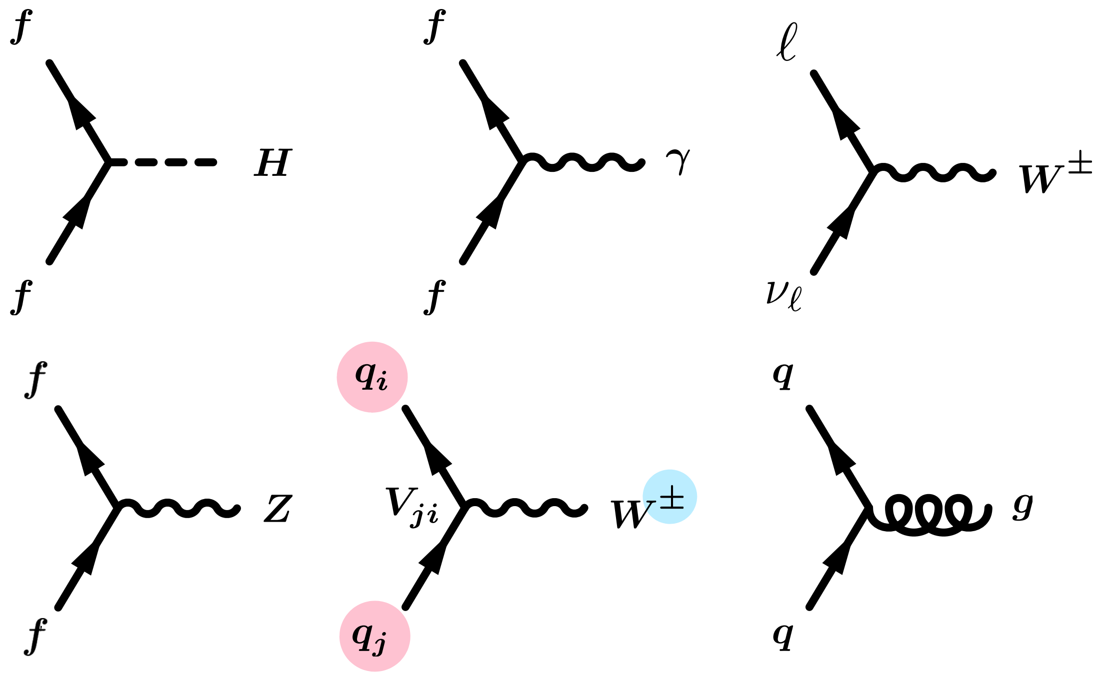
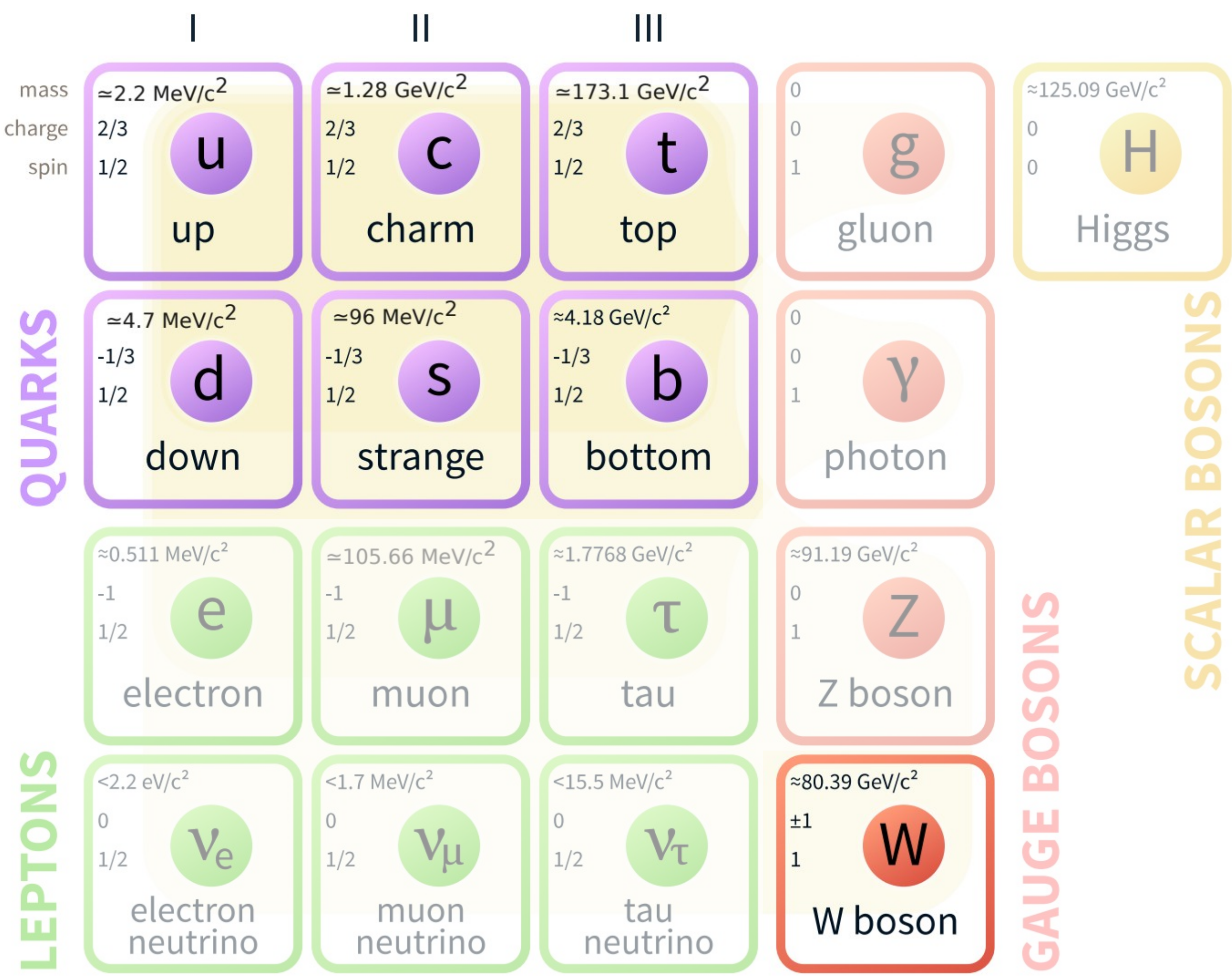
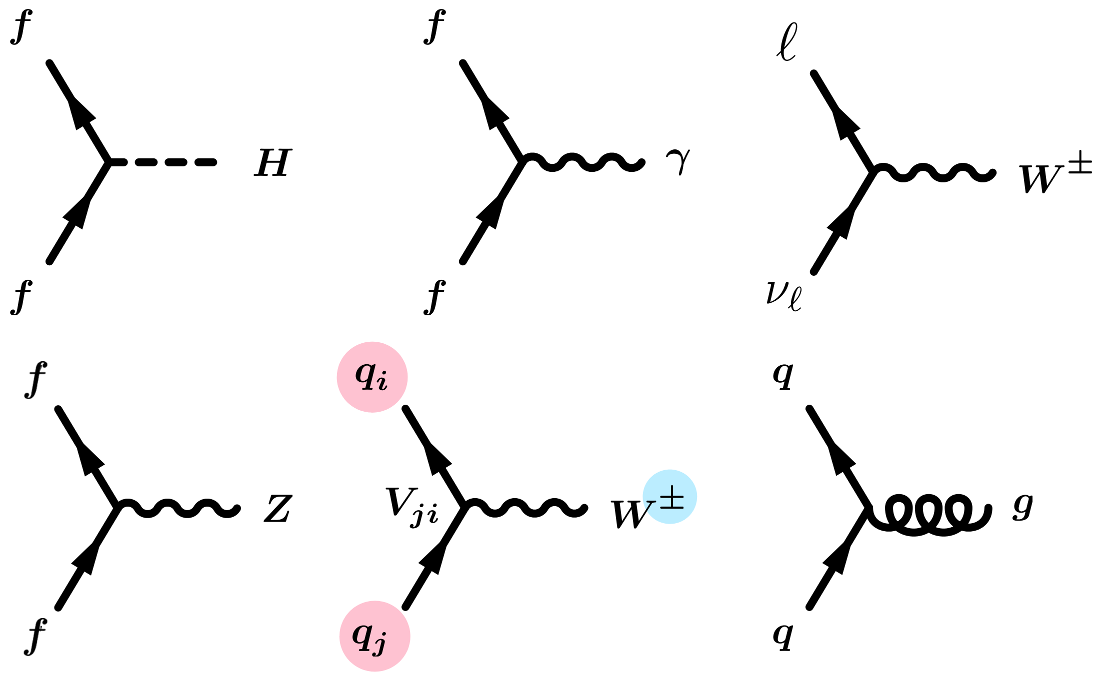




$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

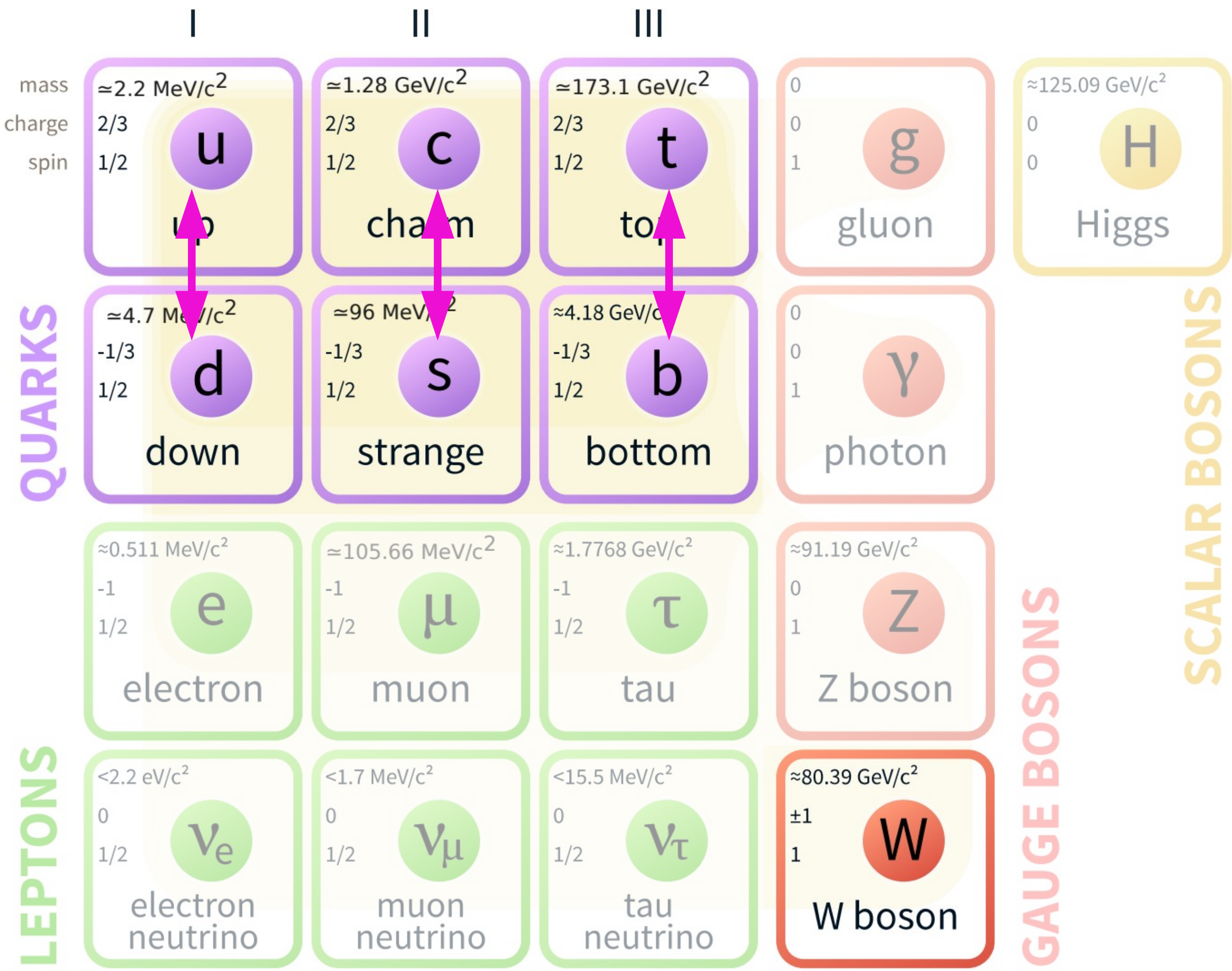
How to change flavour?

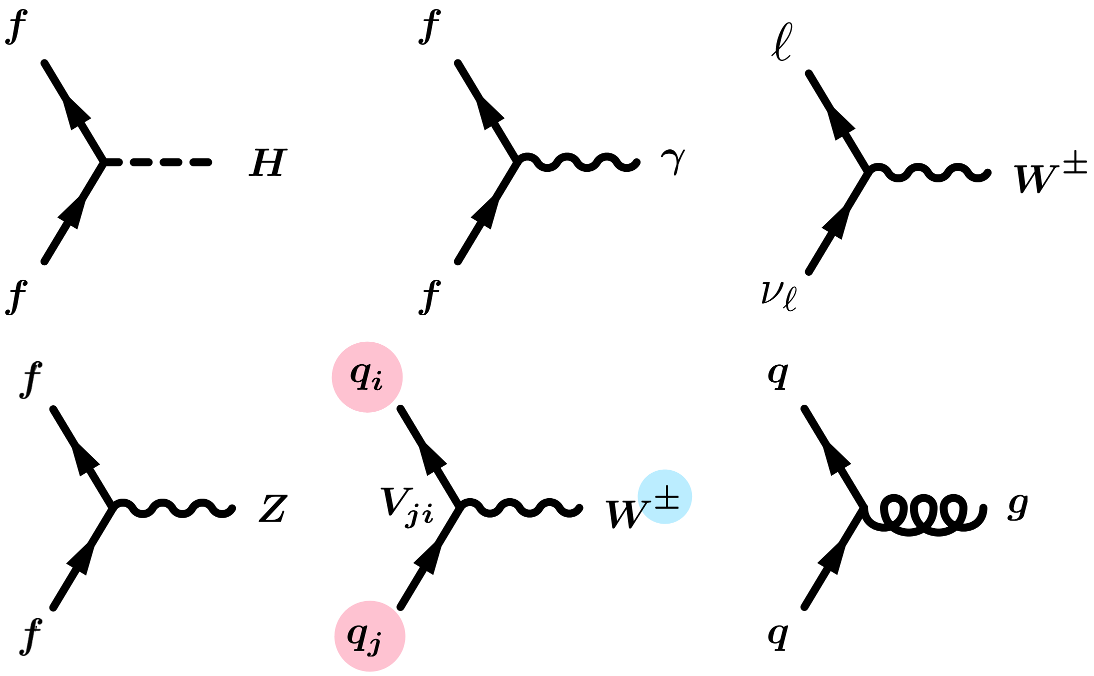




0.974	0.225	0.00351
0.225	0.973	0.0412
0.00867	0.0404	0.999

How to change flavour?





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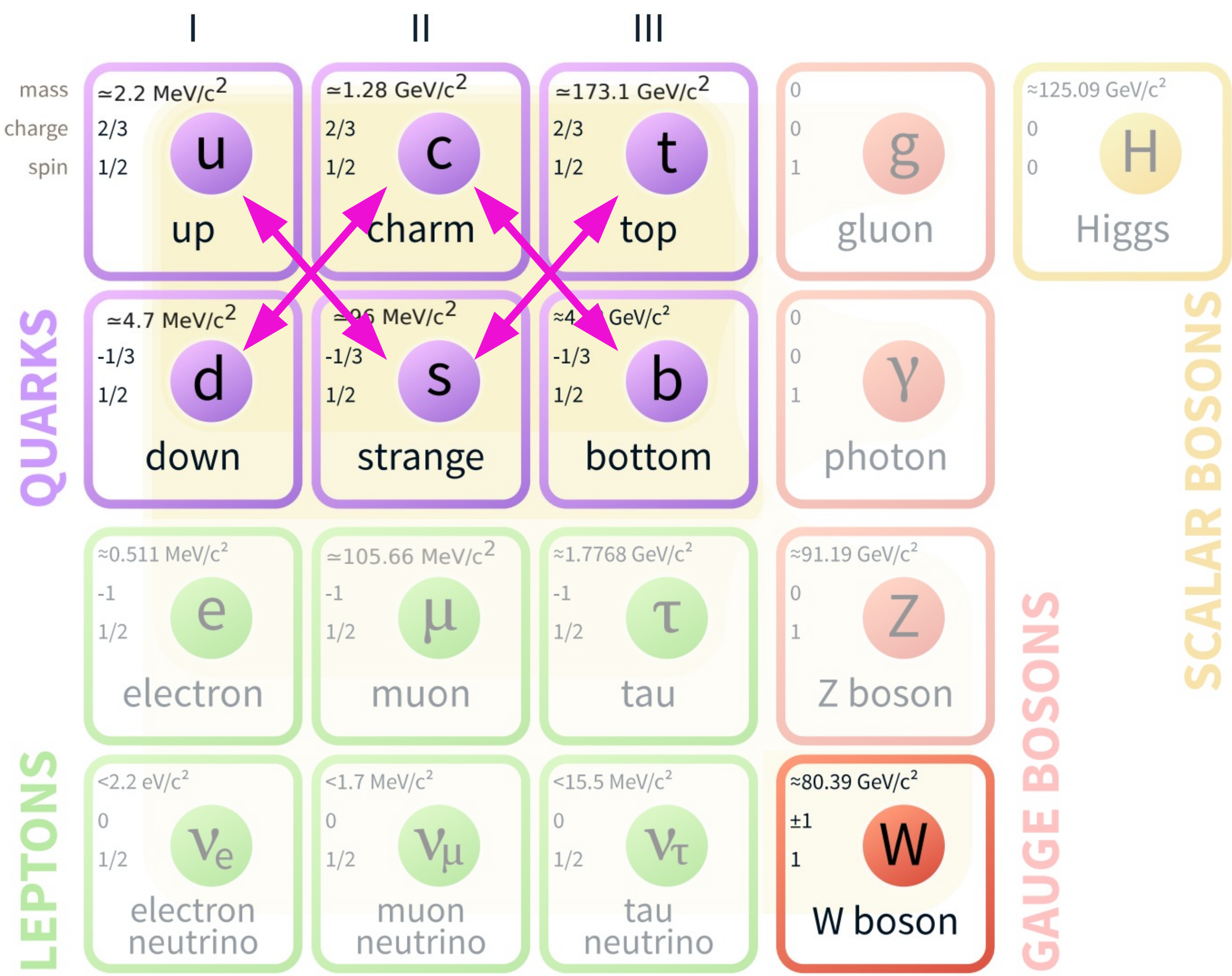

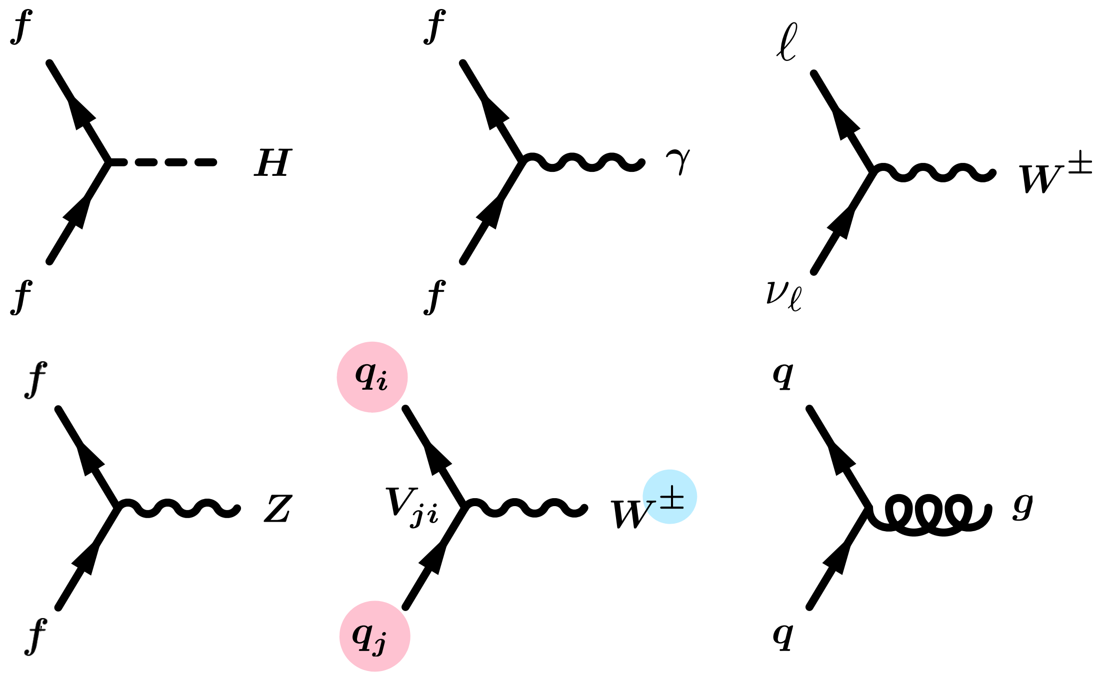

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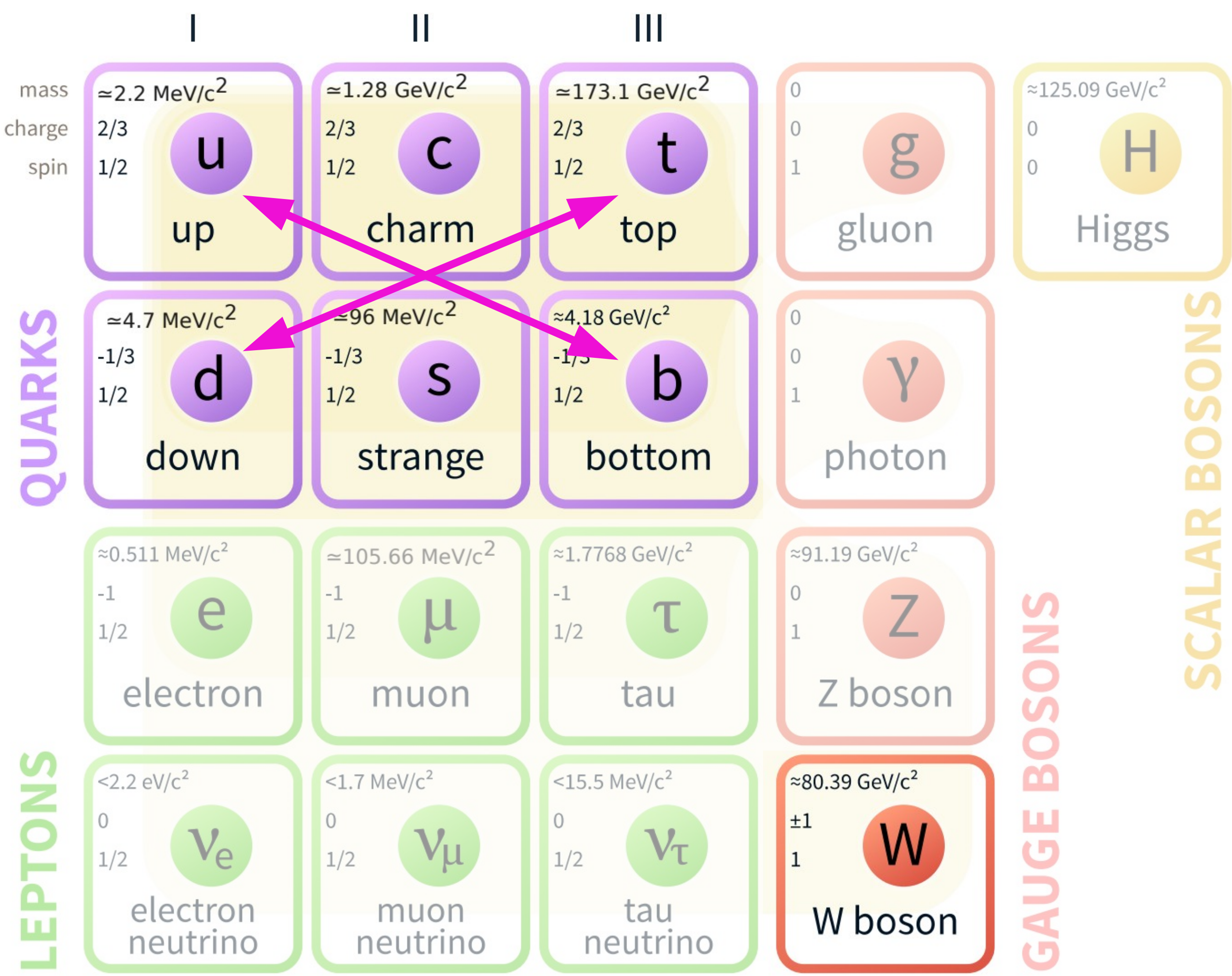

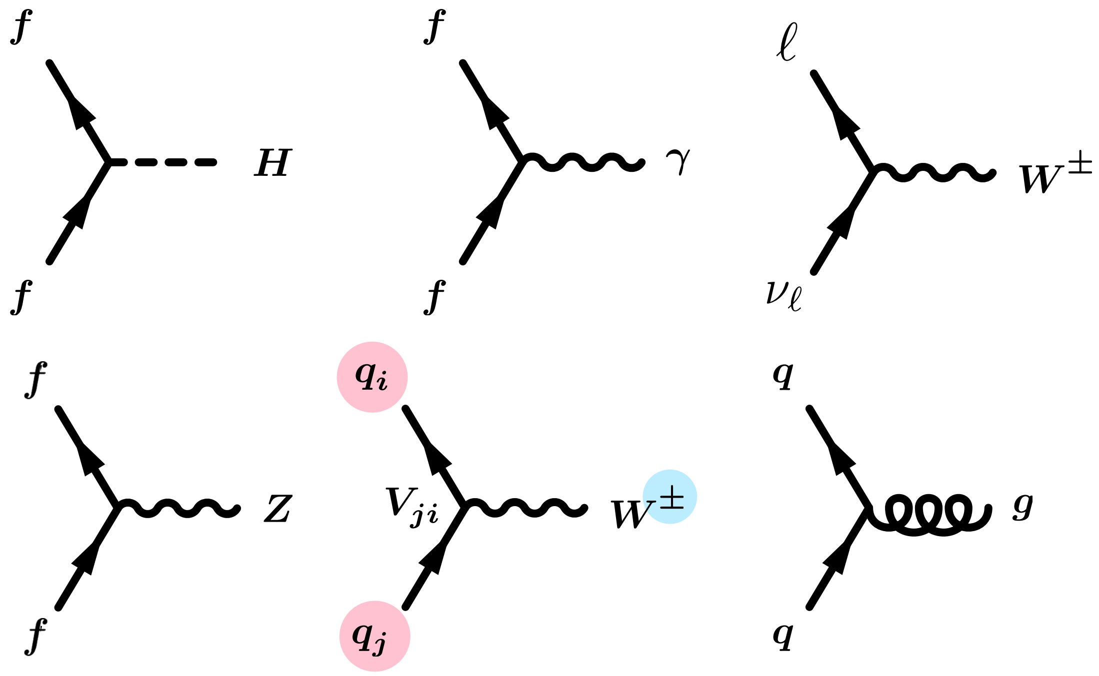

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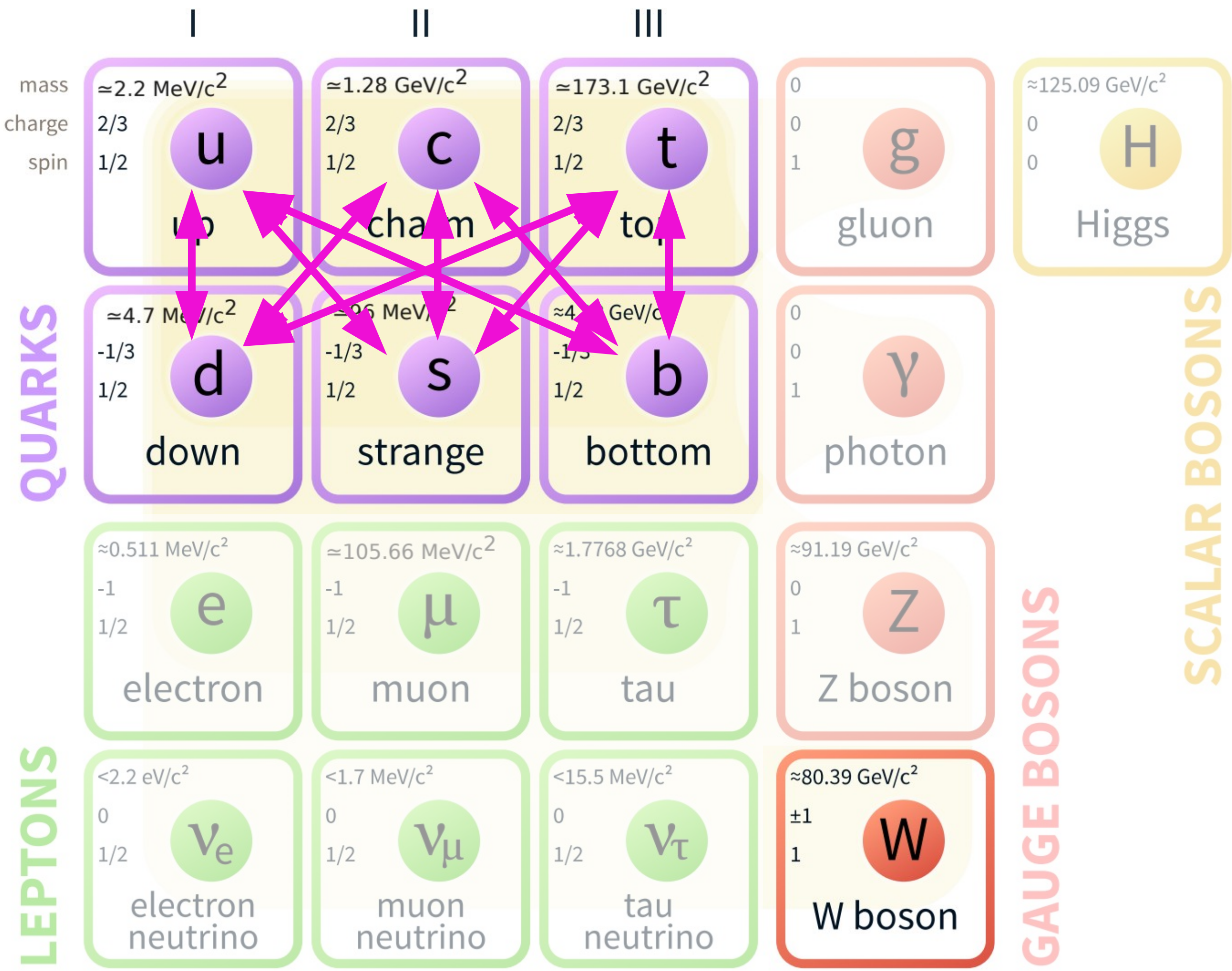
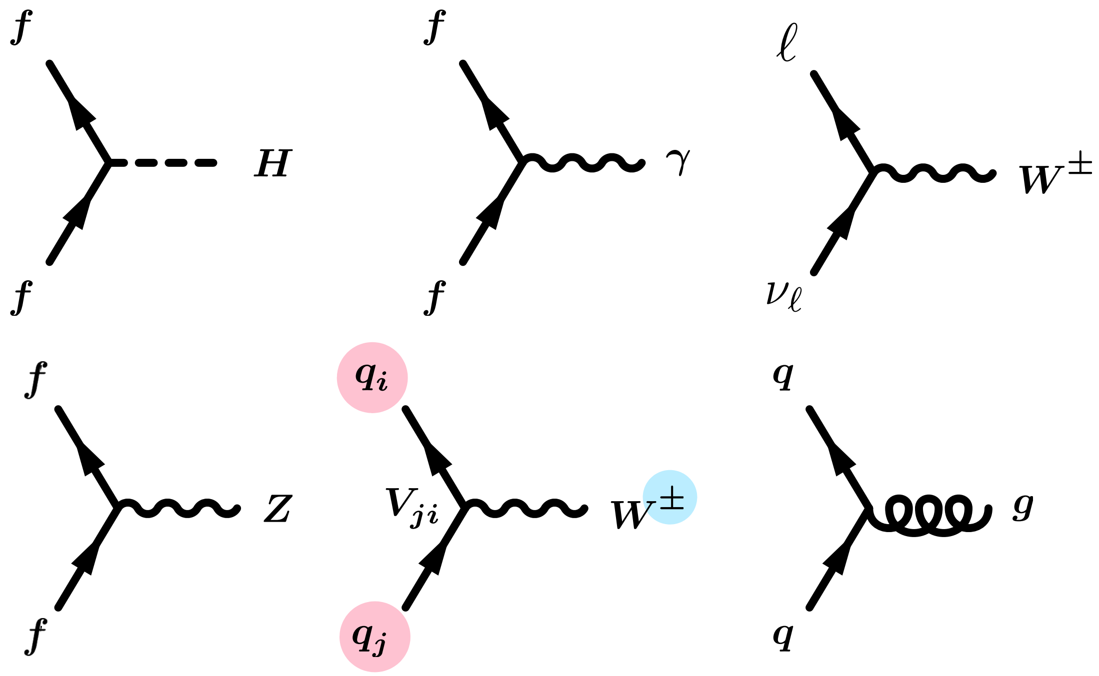
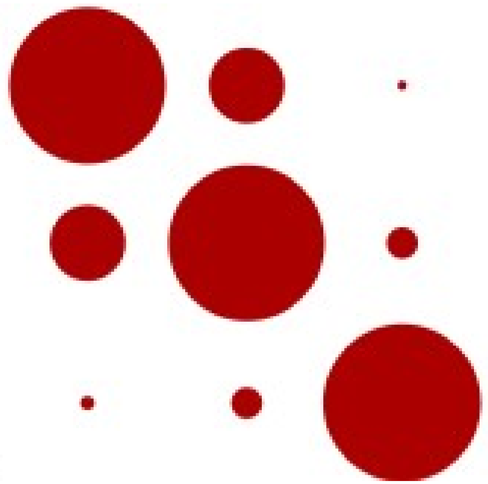


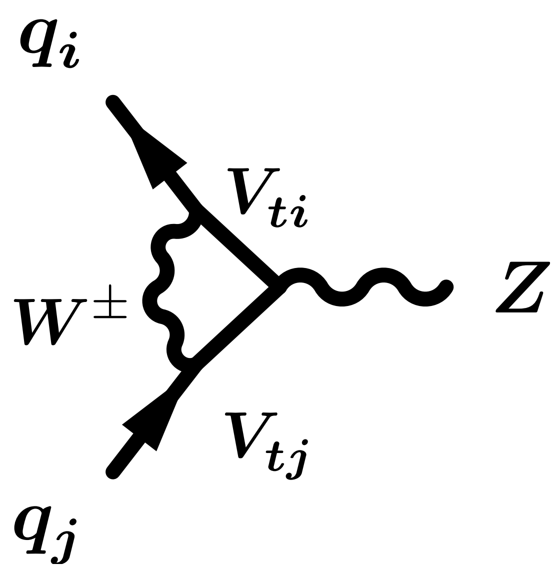


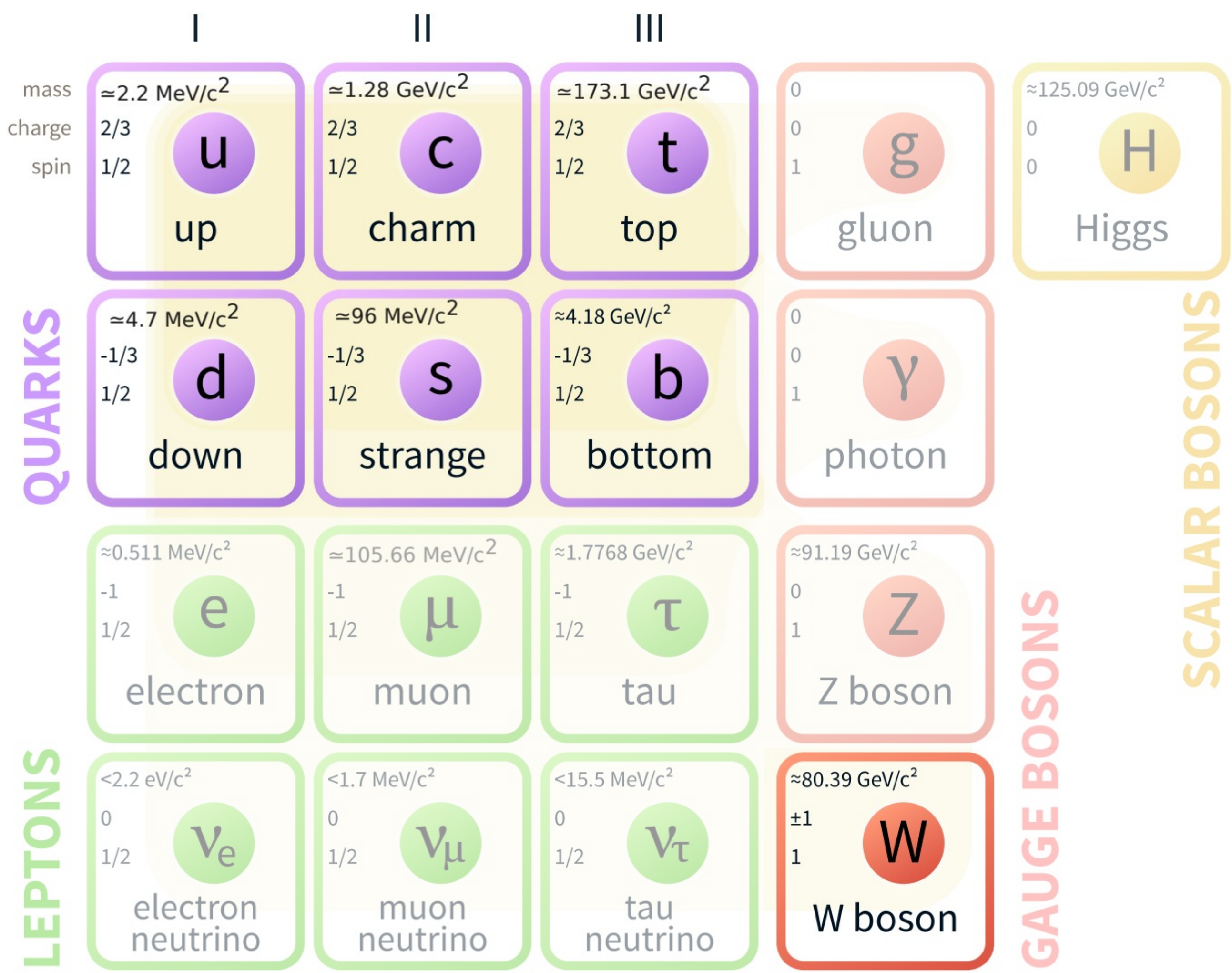
V_{CKM}



Can't change columns directly

- To change column one is forced to change row first.
- Combines three of the SM vertices ∴ **must** involve virtual particles.





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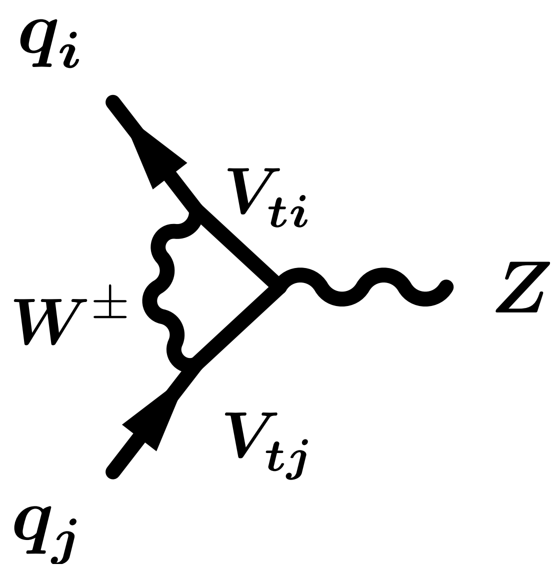
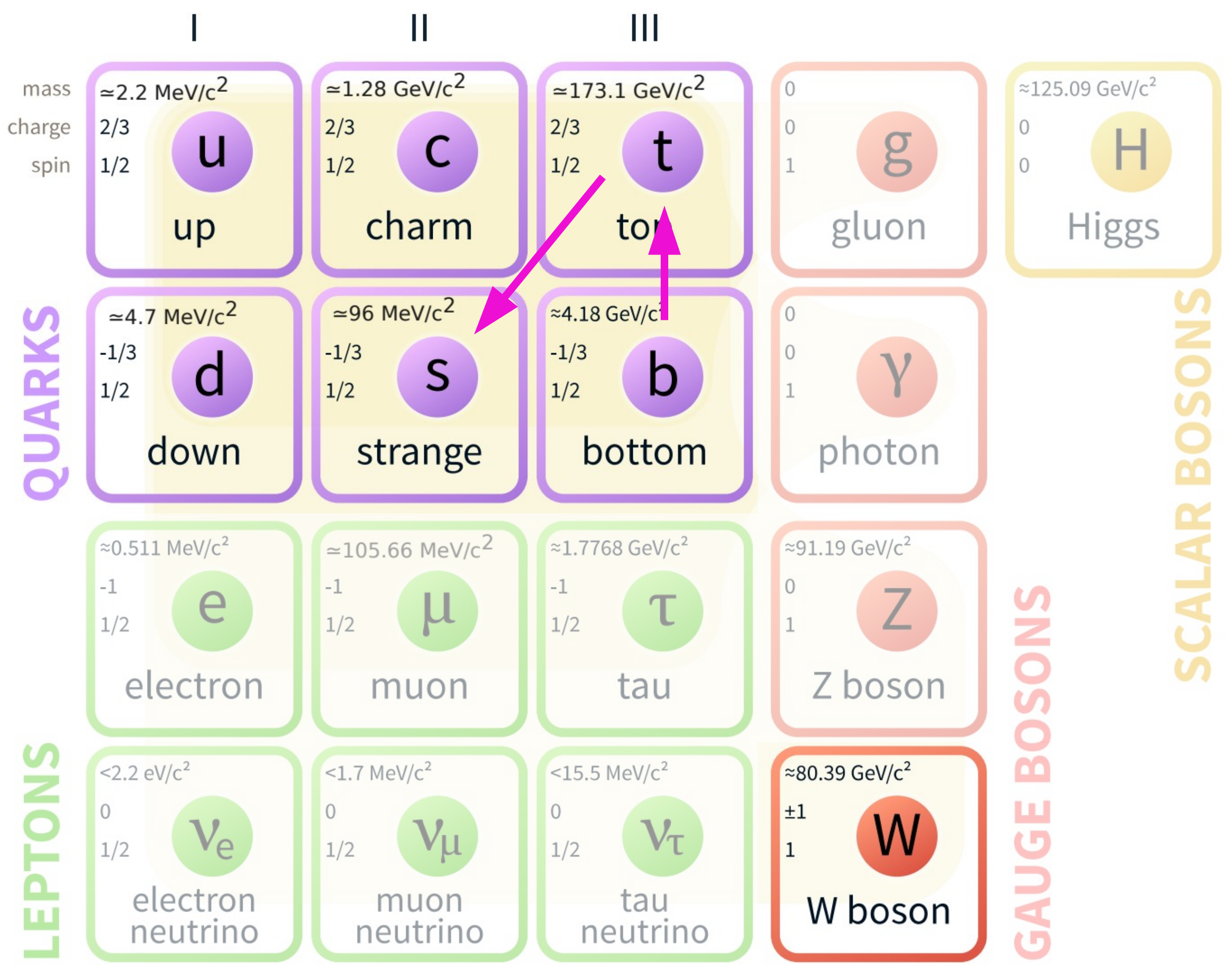


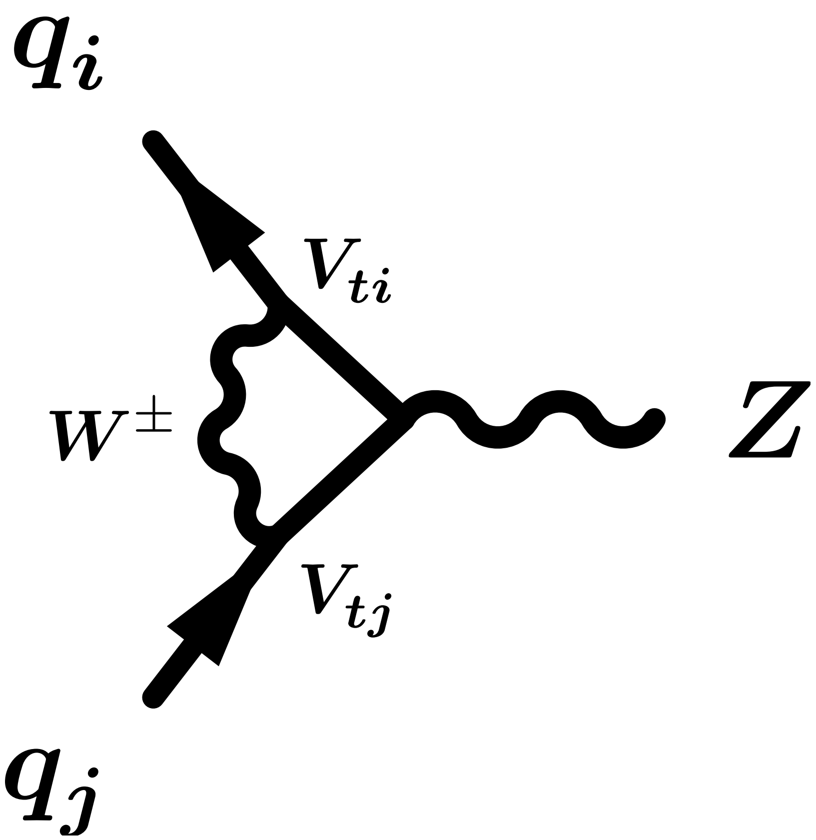


Flavour-changing neutral currents

- I told you flavour physics people love jargon.
- Here is an important one.

- Flavour-changing neutral current (**FCNC**)
- They are famously **forbidden at tree level in the Standard Model**.

- Hopefully that's now clear what it means.



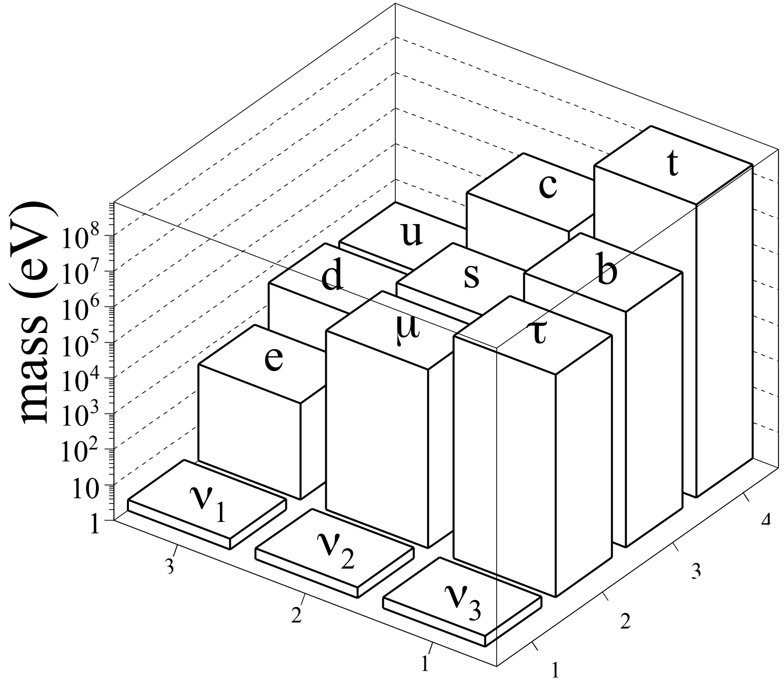
Summary and caveats

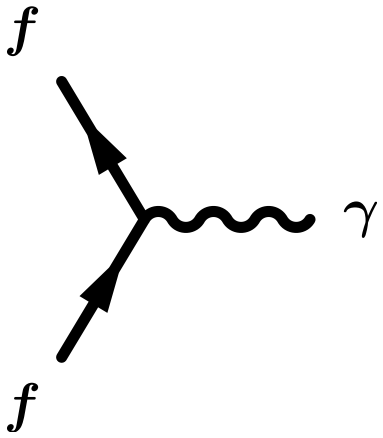
- The Standard Model is a set of rules.
- It’s a little ad-hoc. But it’s the most precise theory we have at the moment.

- All of what I’ve been saying is true “**within the Standard Model**”.
  - If you’re playing according to the SM’s rules.

- We think/hope/expect it’s **not** really how nature is.
- It’s just our best guess at the moment.

You should know: there are problems with the Standard Model





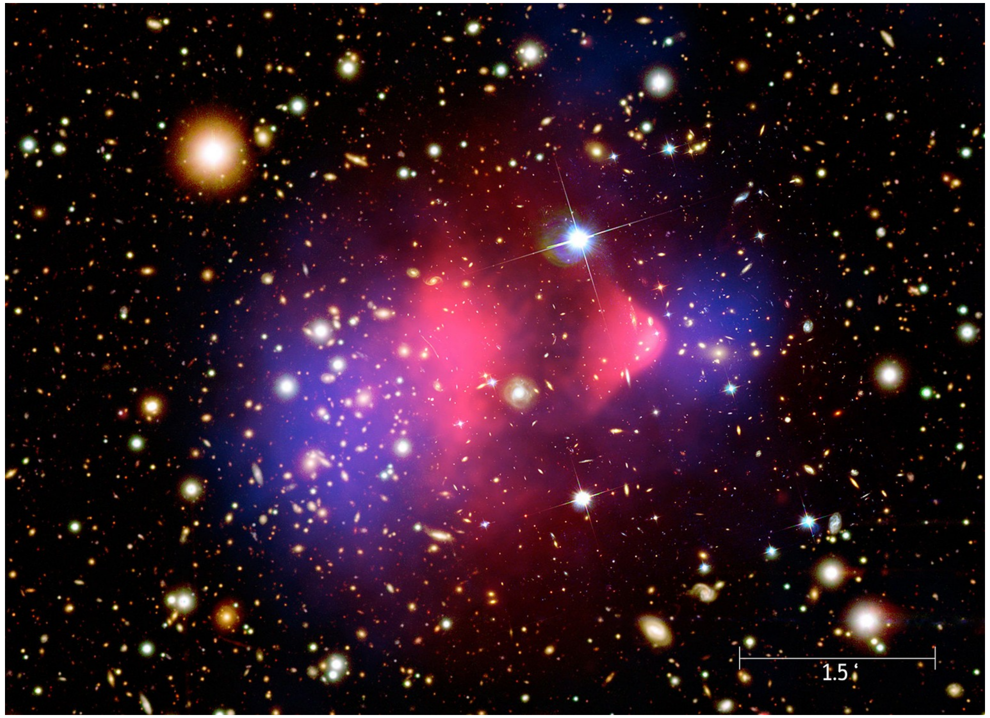
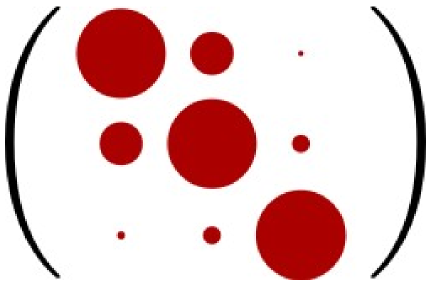


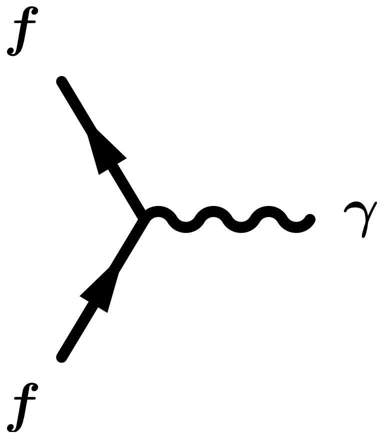
Photo: NASA/Chandra X-ray Observatory / Wikimedia Commons

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} =$$

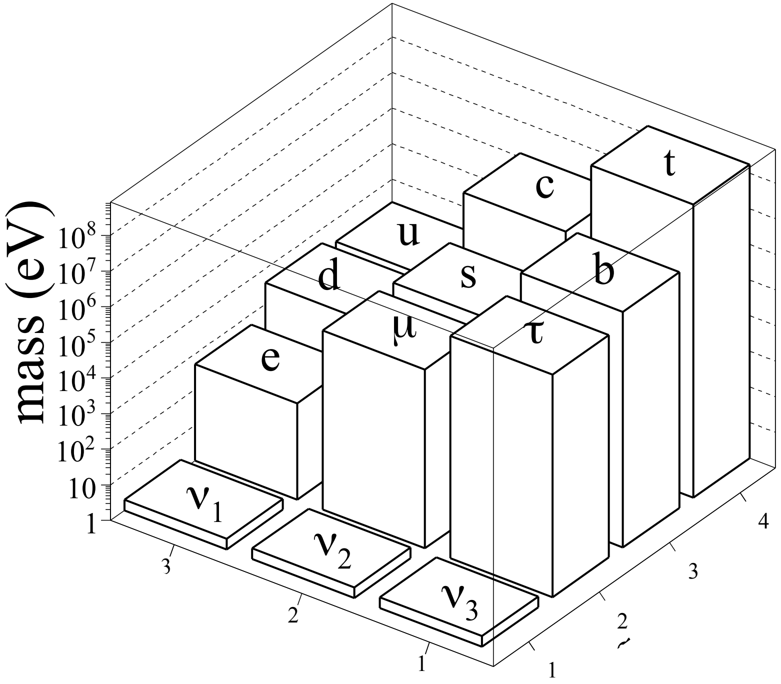


You should know: there are problems with the Standard Model

Matter-antimatter
asymmetry (in nature)



Mass values
(in particular: neutrino masses)



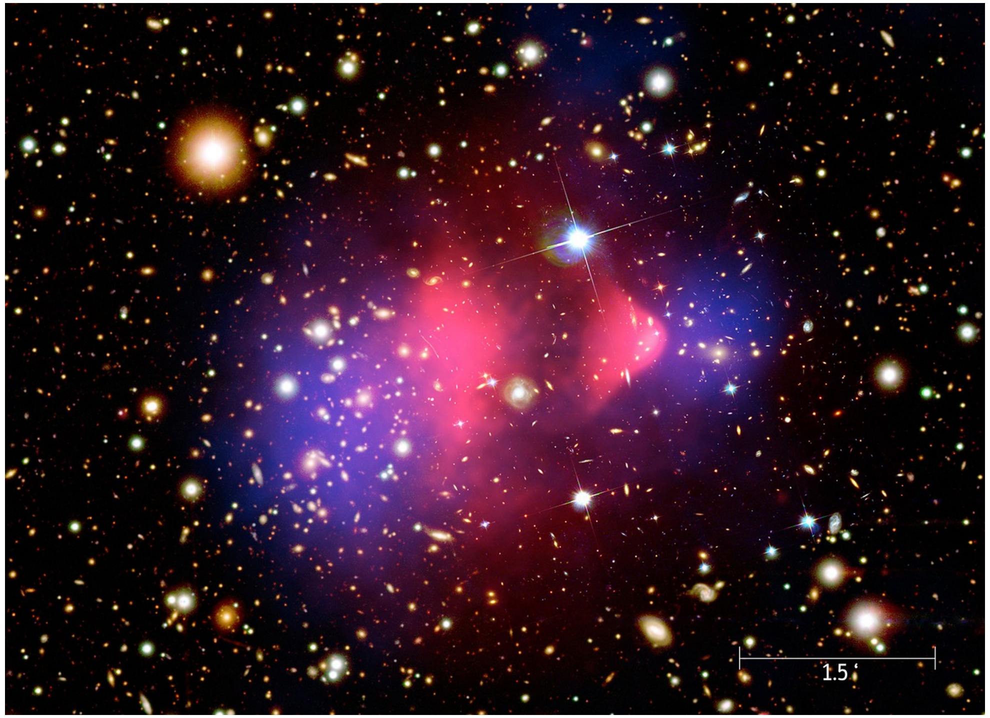
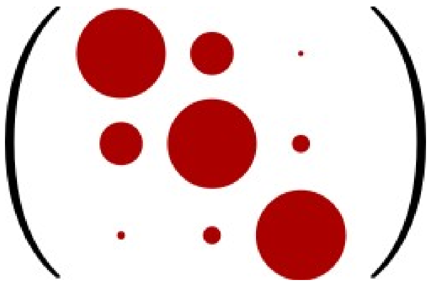


Photo: NASA/Chandra X-ray Observatory / Wikimedia Commons

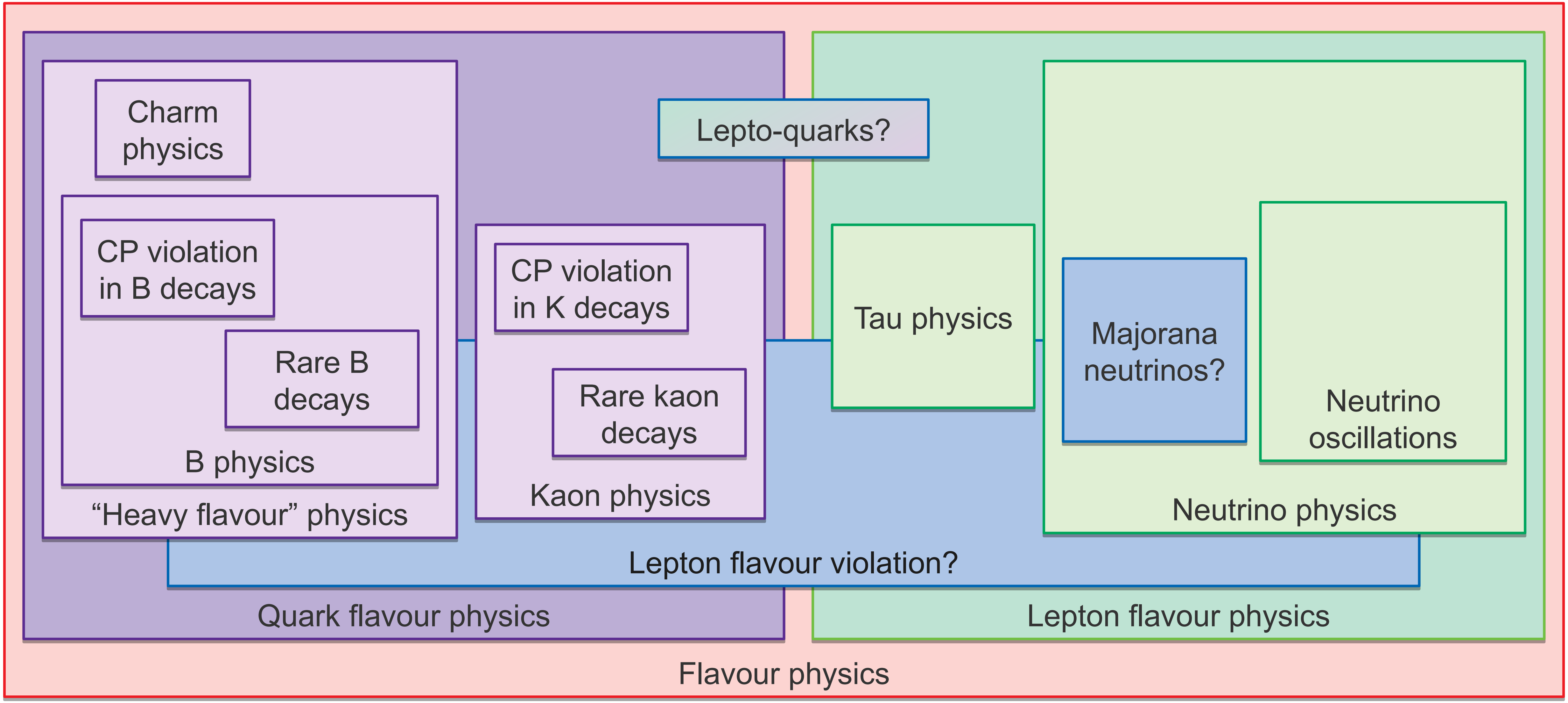
Dark matter

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} =$$

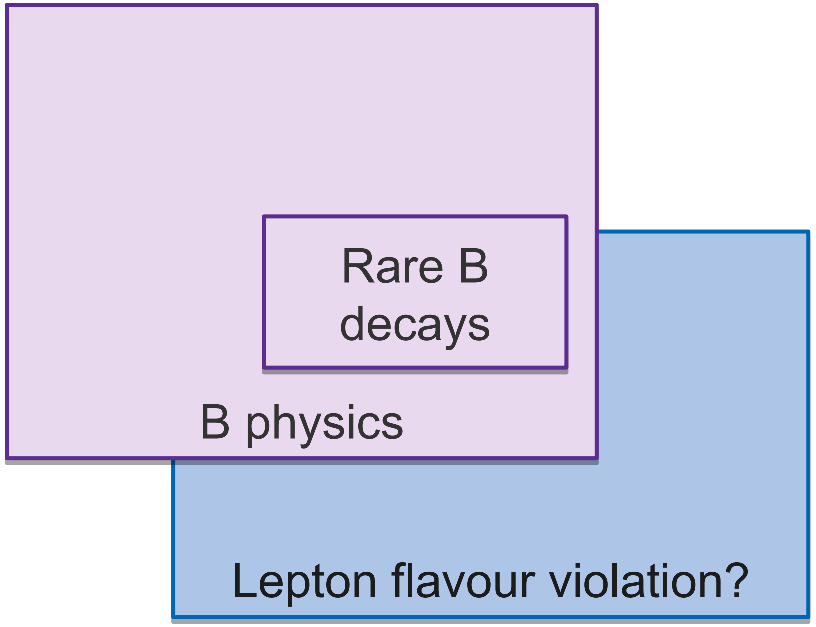


CKM Structure

I hope this diagram is helpful



Now we specialise



- I want to focus on active research in flavour physics.
- The main sub-field is basically B physics.
  - It’s what most people think of a flavour physics.
  - It’s also what you probably would do a master/PhD in.
  - It’s what I can talk about.

0. What?
1. Experiments
1. Observables
2. Rare decays and anomalies
2. The field in 202X

Experiments

Dramatis personae

- B factory
  - Collides e^+e^- at precisely the energy to create an ϒ(4S).
  - An ϒ(4S) is a meson made of a bb pair. It decays almost 100% to BB.
  - … Hence “factory”.

- What other designs are there?
  - Fixed target (HERA B)
  - “Pseudo” fixed target (LHCb)
  - General purpose detectors (CDF, D0, CMS, ATLAS)

$$\Upsilon(b\bar{b})$$
$$B^+(\bar{b}u)$$
$$B^-(b\bar{u})$$
$$B^0(\bar{b}d)$$
$$\bar{B}^0(b\bar{d})$$
$$B^0_s(\bar{b}s)$$
$$\bar{B}^0_s(b\bar{s})$$

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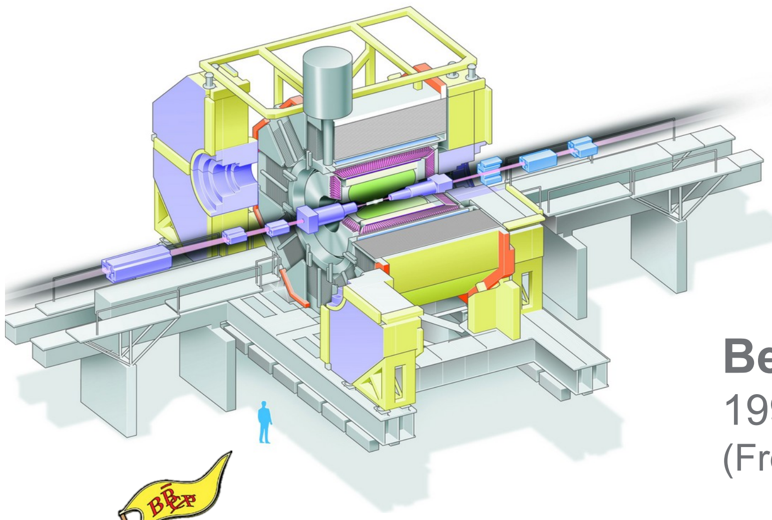
$$B^0(\bar{b}d)$$
$$\bar{B}^0(b\bar{d})$$
$$B_s^0(\bar{b}s)$$
$$\bar{B}_s^0(b\bar{s})$$

The B factories

$e^+e^- \to \Upsilon(4S) \to B\bar{B}$

$\sqrt{s}$ = 10.58 GeV (asymmetric beams)

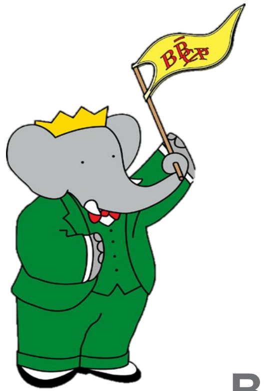
$B\bar{B}$ system is clean and well constrained



Belle

1999–2010, Japan

(French for ‘beauty’)



BaBar

1999–2008, USA

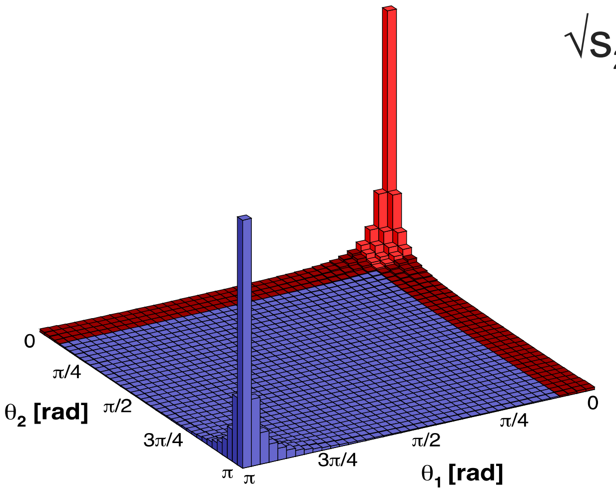
(The king of the elephants, name sounds like BB)

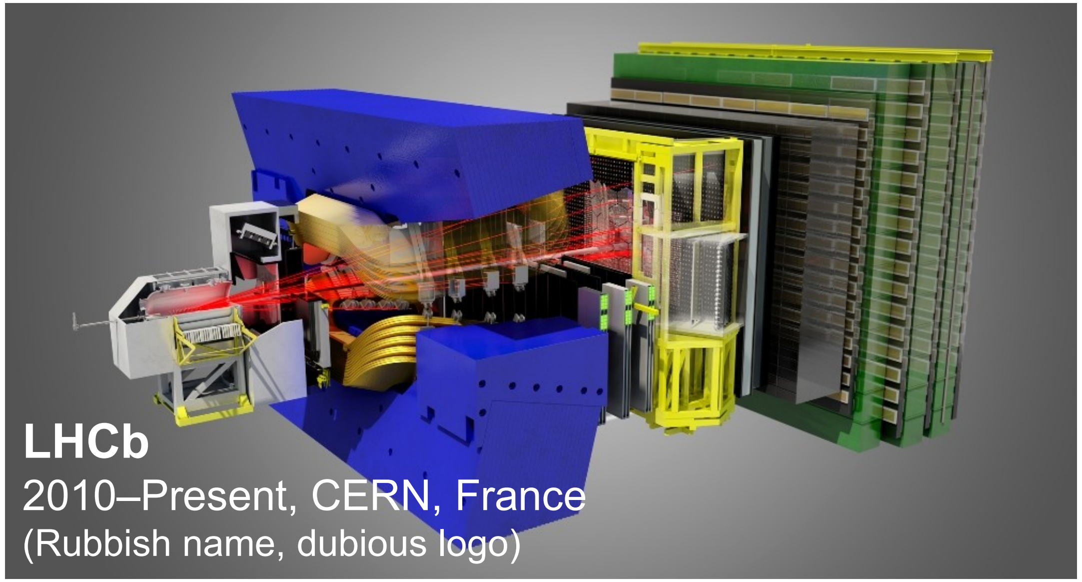
LHC

$pp \to b\bar{b} + ?$

$\sqrt{s}_{2016}$ = 6.5+6.5 TeV

$B\bar{B}$ system is not well constrained





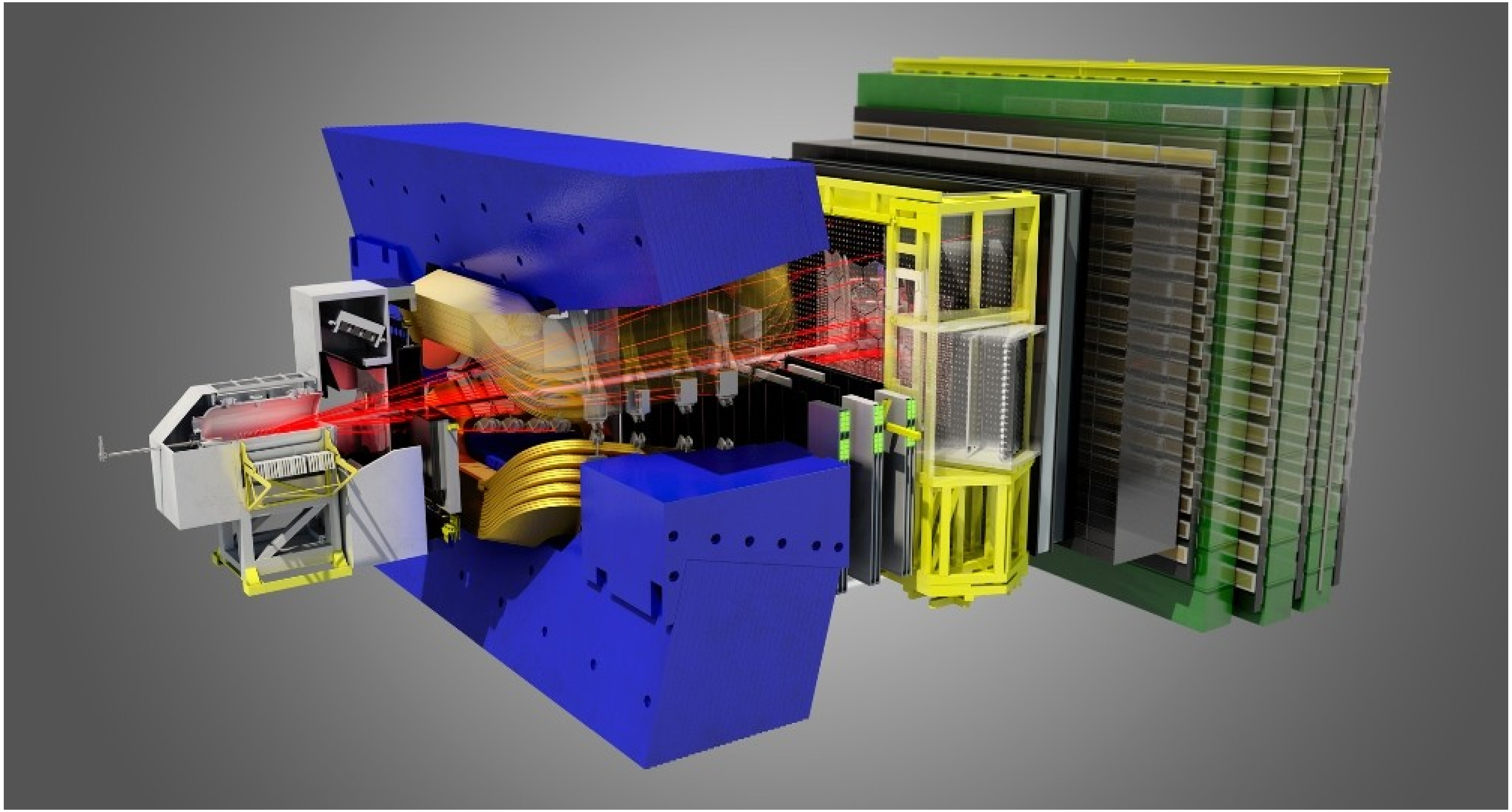
LHCb

2010–Present, CERN, France

(Rubbish name, dubious logo)

LHCb

A little bit more detail



LHCb

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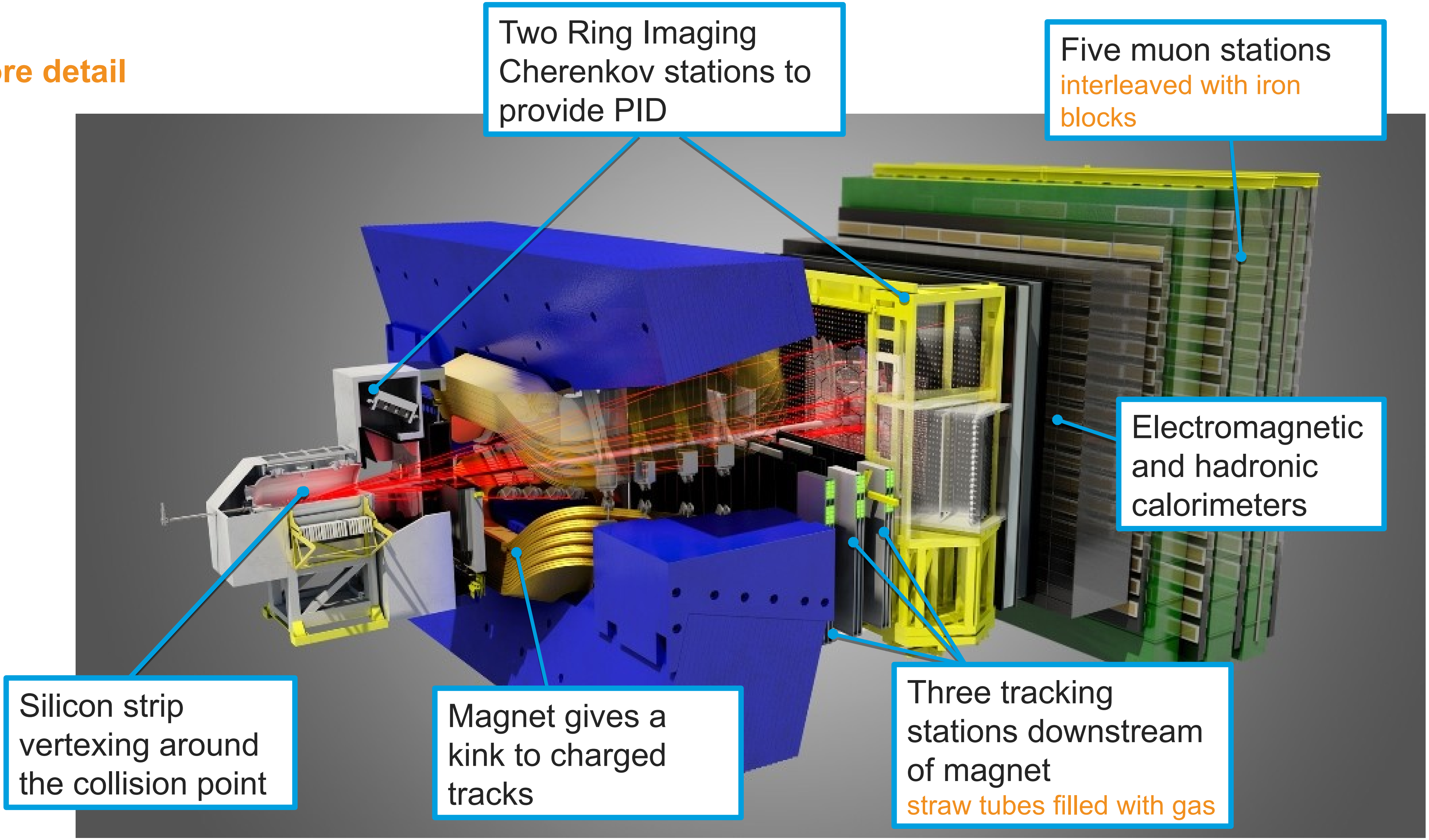
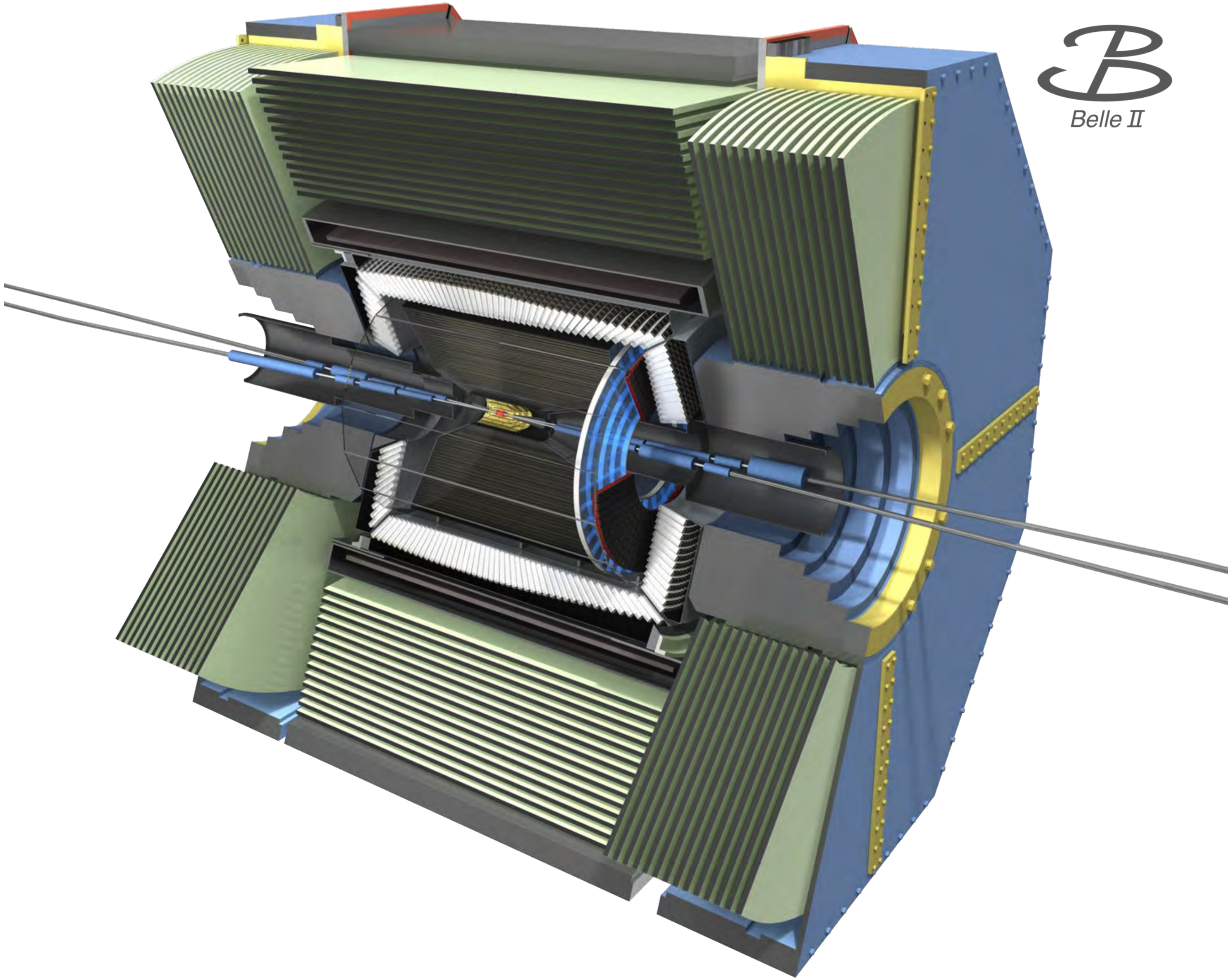


Belle II



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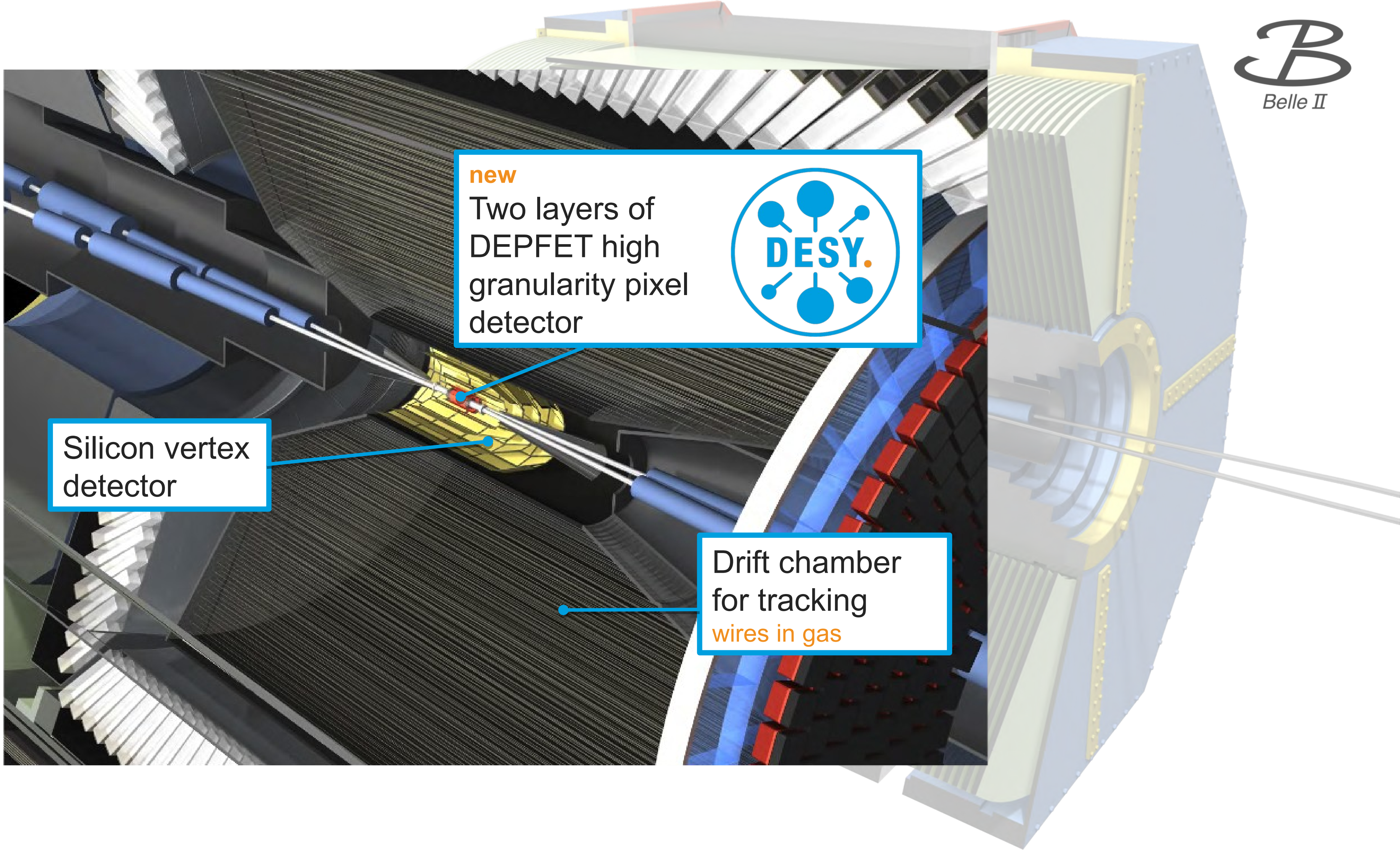
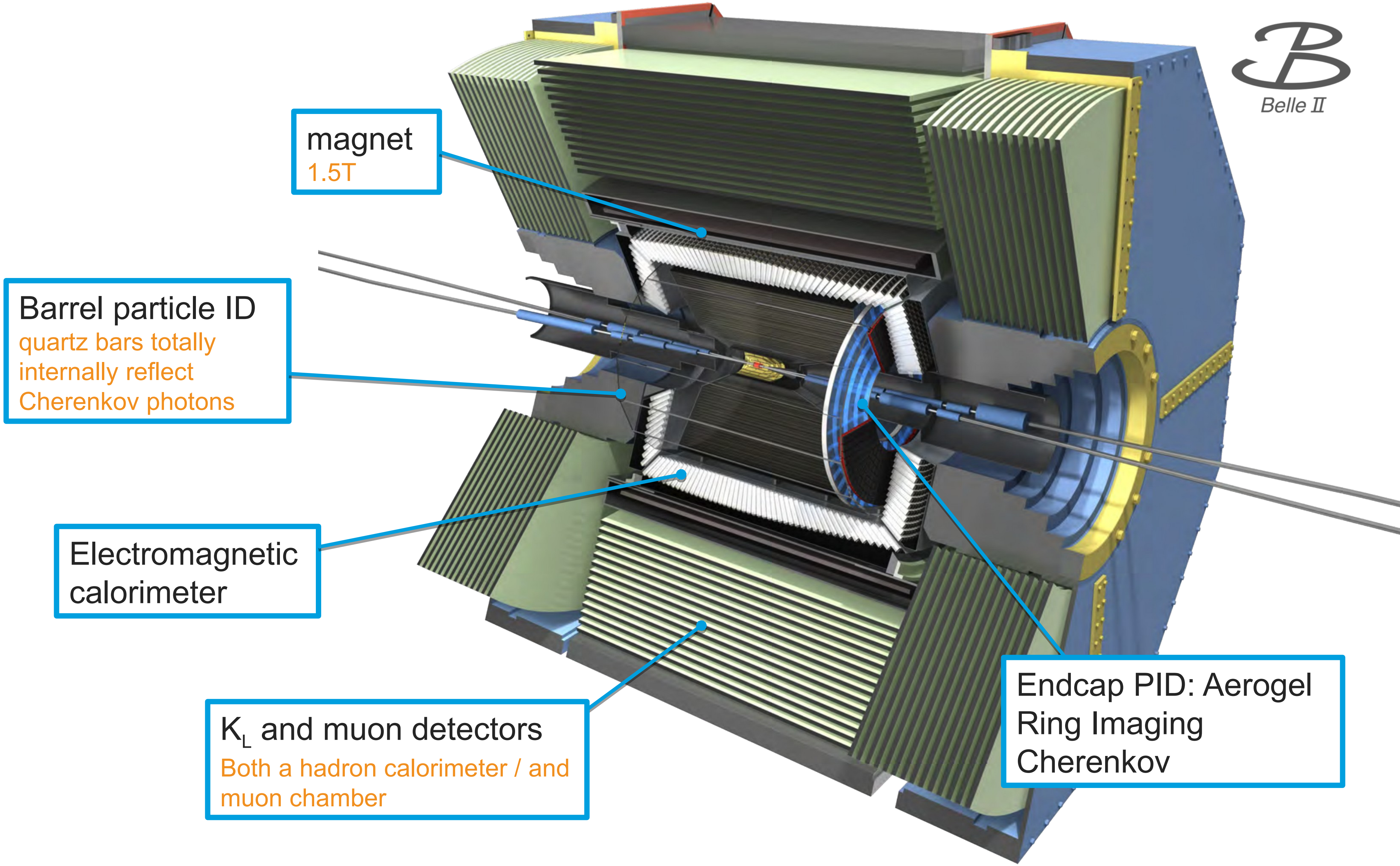

new
Two layers of DEPFET high granularity pixel detector
Silicon vertex detector
Drift chamber for tracking
wires in gas

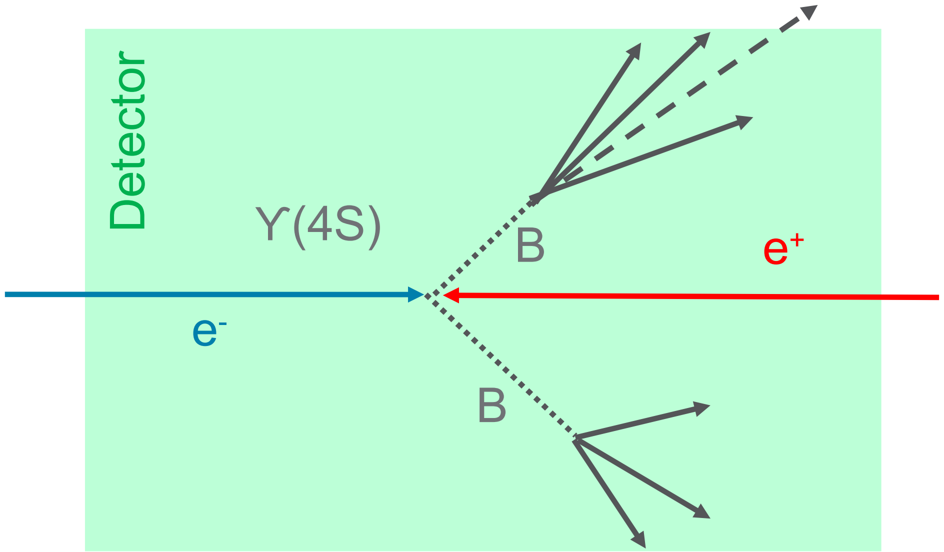
Belle II


magnet
1.5T
Barrel particle ID
quartz bars totally internally reflect Cherenkov photons
Electromagnetic calorimeter
K_L and muon detectors
Both a hadron calorimeter / and muon chamber
Endcap PID: Aerogel Ring Imaging Cherenkov
Belle II

The essentials

The B factories

BB system is clean and well constrained



- Collision energy is well known
- Good at neutral particles / missing energy / neutrino final states / taus

BELLE

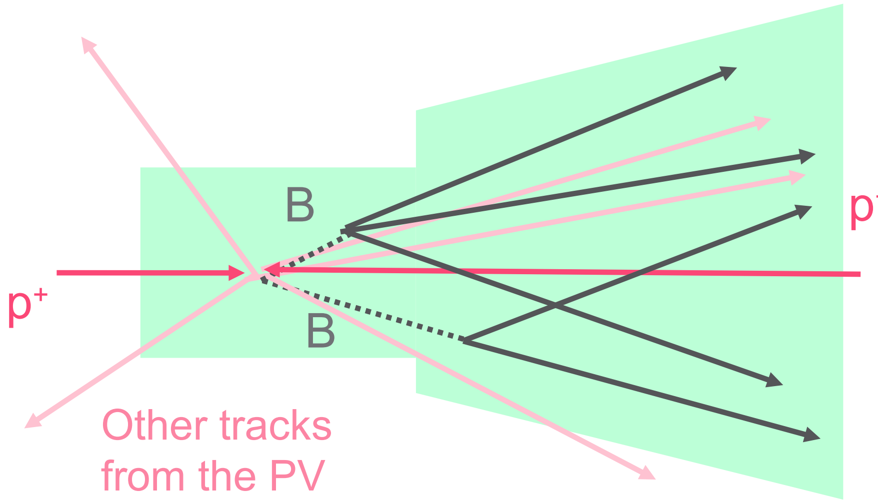
Belle II

LHC

pp ⟶ bb + ?

$\sqrt{s}_{2016}$ = 6.5+6.5 TeV

BB system is not well constrained



- Collision energy not well known
- High energy, running longer @ high production
- Very good at muons

- Single particle tracking
- Good at vertexing B decays
- Good at hadron identification

0. What?
1. Experiments
1. Observables
2. Rare decays and anomalies
2. The field in 202X

Observables

Ratio, difference, asymmetry

- Almost all flavour physics papers are measuring some kind of ***constructed observable***.
- The branching ratio / fraction is the ratio of the rate decay for B → f to all decays of the B.

$$\mathcal{B}(B \to f) \equiv \frac{\Gamma(B \to f)}{\Gamma_{\mathrm{T}}}$$
$$= \frac{N_{B\to f}}{\epsilon_{B\to f}} \frac{\epsilon_{\mathrm{norm.}}}{N_{\mathrm{norm.}}} \mathcal{B}(\mathrm{norm.})$$

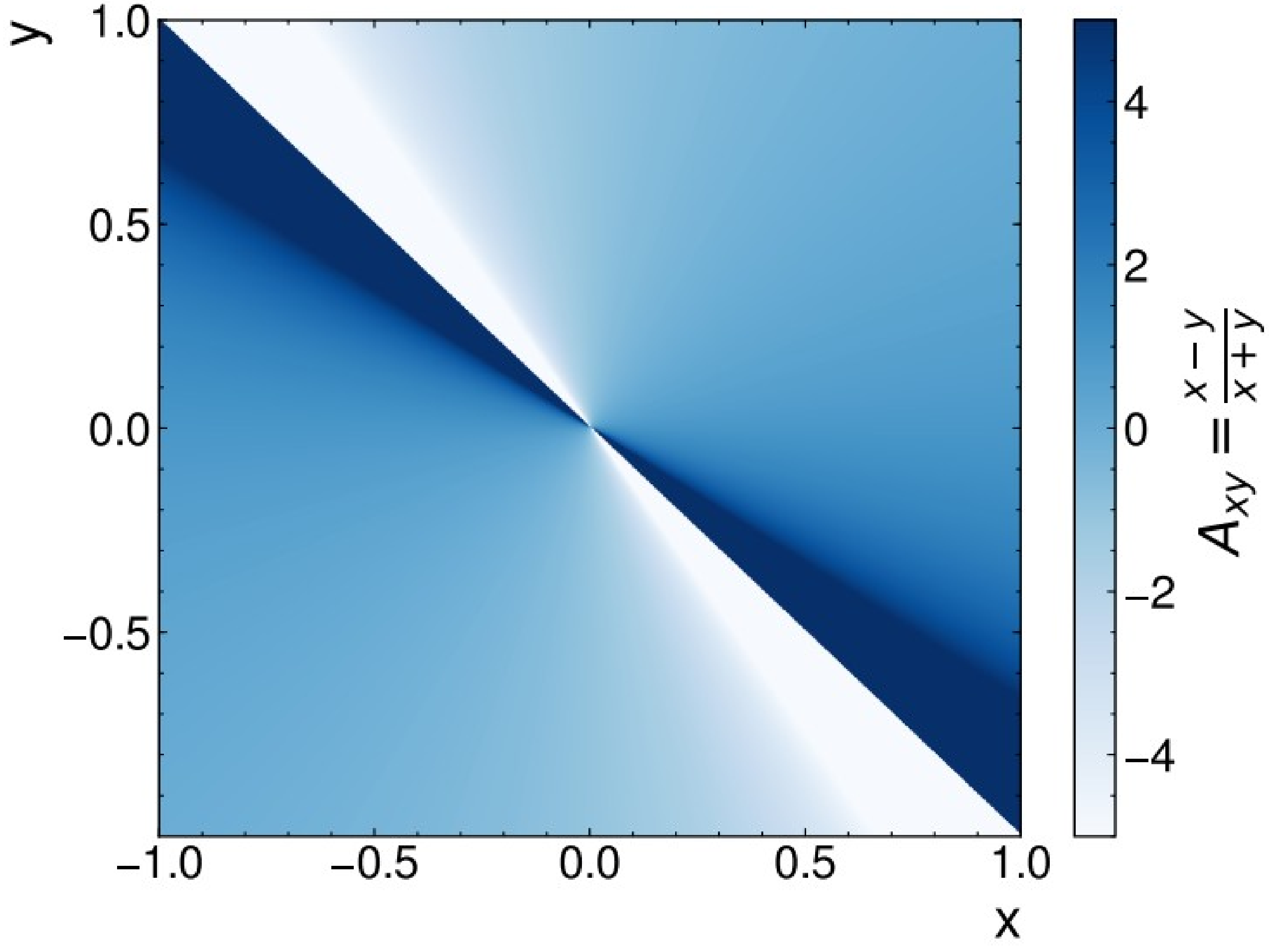
- It's very common to make either: a **ratio**, a **difference**, or **asymmetry**, or some combination of the three.
- The first two are easy. Usually denoted "R" and Δ.
- Examples: R_{D*} R_{K*}, angular observables.

Observables

Ratio, difference, asymmetry

- Often we form asymmetries
  - “CP asymmetries”
  - or “isospin asymmetries”
  - or “time-dependent-CP-asymmetries”.
- These are all the same basic quantity **formed between rates of different decay modes**.
- That quantity is the difference over the sum.

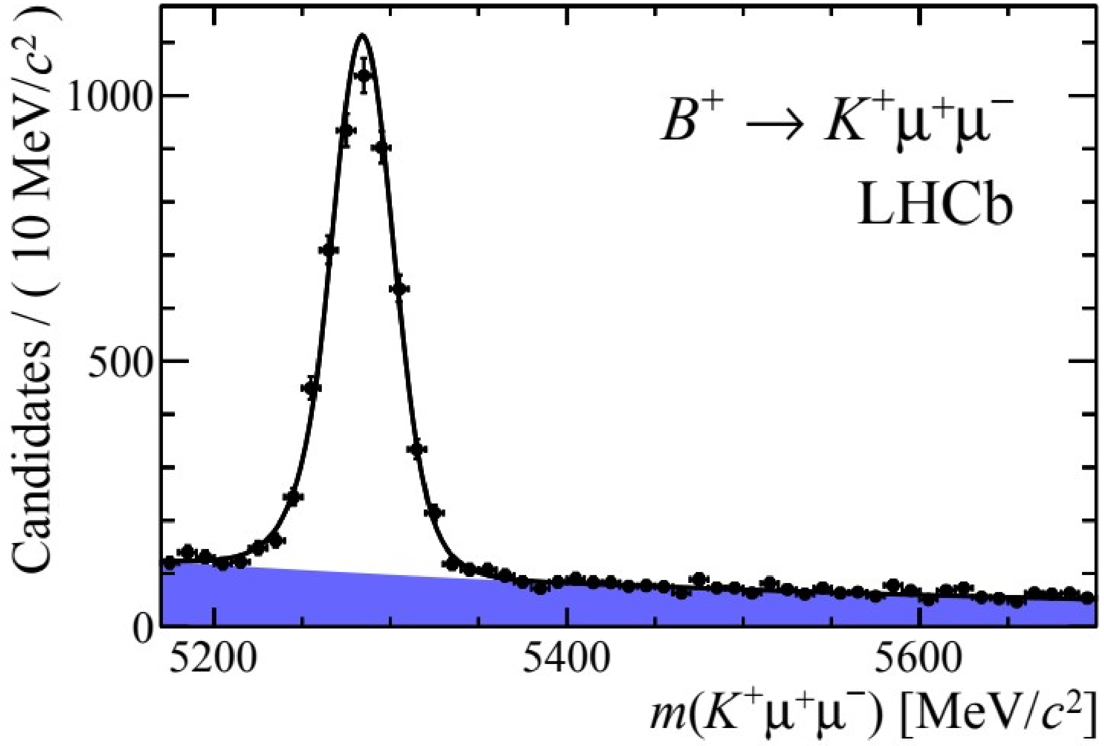
$$\frac{x-y}{(x+y)}$$



How to do a b-physics measurement

A template

1. Figure out a smart observable to measure.
   Smart means:
   - Minimises experimental uncertainties.
   - Is sensitive to some kind of extension to the SM –or– noone else ever did it before.
2. Look for candidate B meson decays for whatever final state you care about.
3. Make some event selection cuts to minimise the background.
4. Make a histogram of something (probably something like the **invariant mass**).
5. Either count the candidates you have, or fit signal + background model → returns you a “yield”.
6. Relate the yield or fit parameters to your observable.



$$m_{K\mu\mu} \equiv \sqrt{((p_K + p_\mu + p_\mu)^\alpha\,(p_K + p_\mu + p_\mu)_\alpha}$$

0. What?
1. Experiments
1. Observables
2. **Rare decays and anomalies**
2. The field in 202X

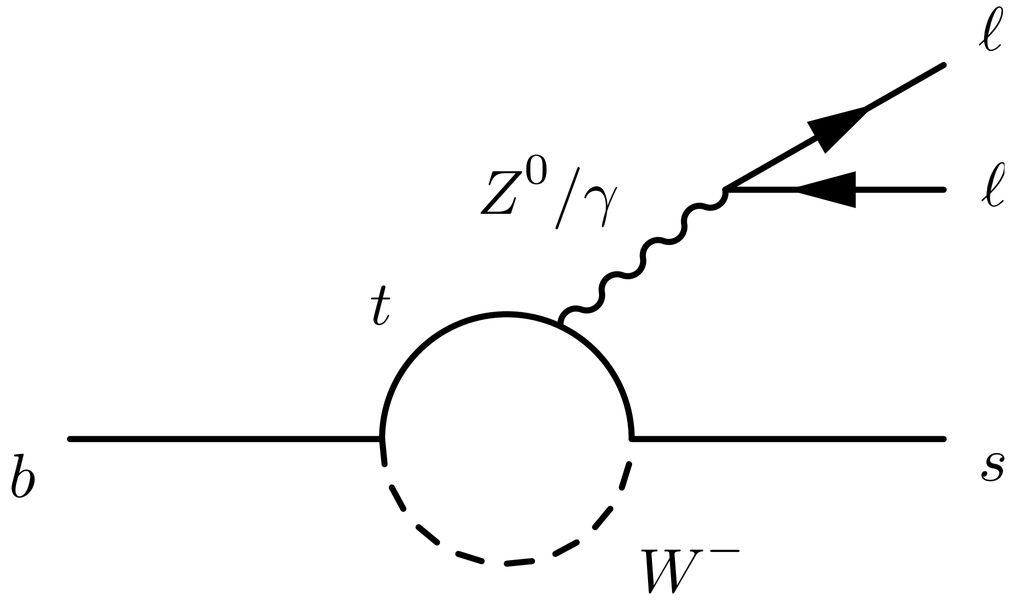
Photo: Godot13 / Wikimedia Commons


Photo: Godot13 / Wikimedia Commons

Photo: Godot13 / Wikimedia Commons

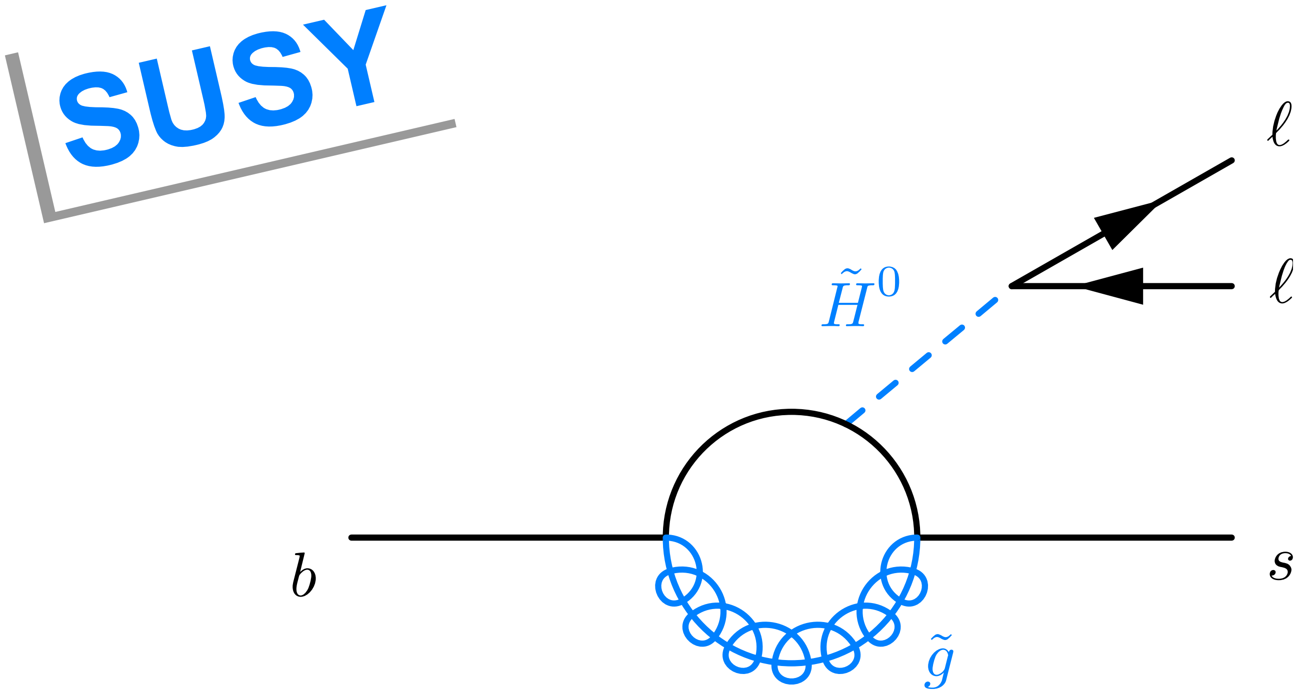
$b \to s\ell\ell$

A hot topic



b → sℓℓ

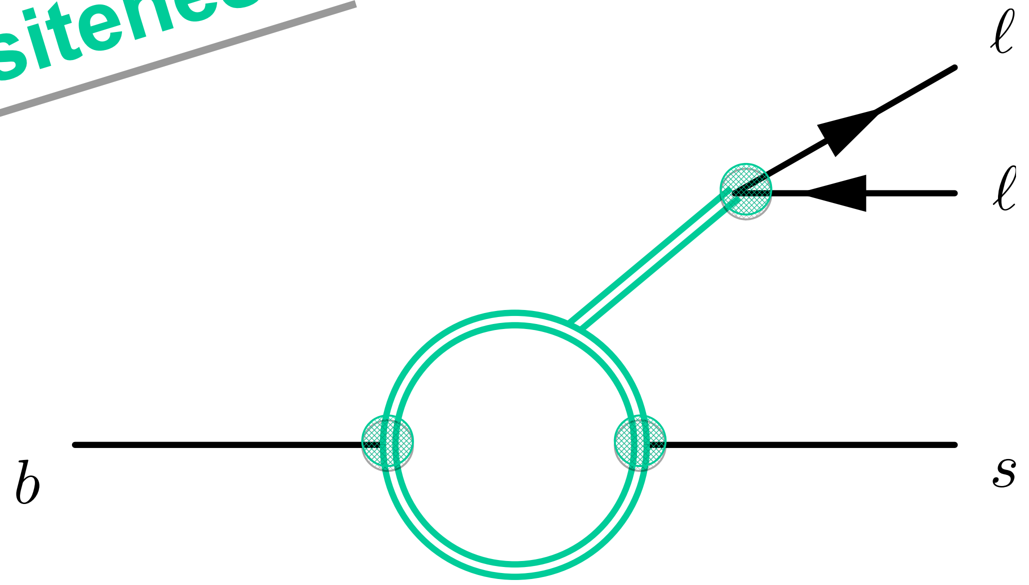
A hot topic



b → sℓℓ

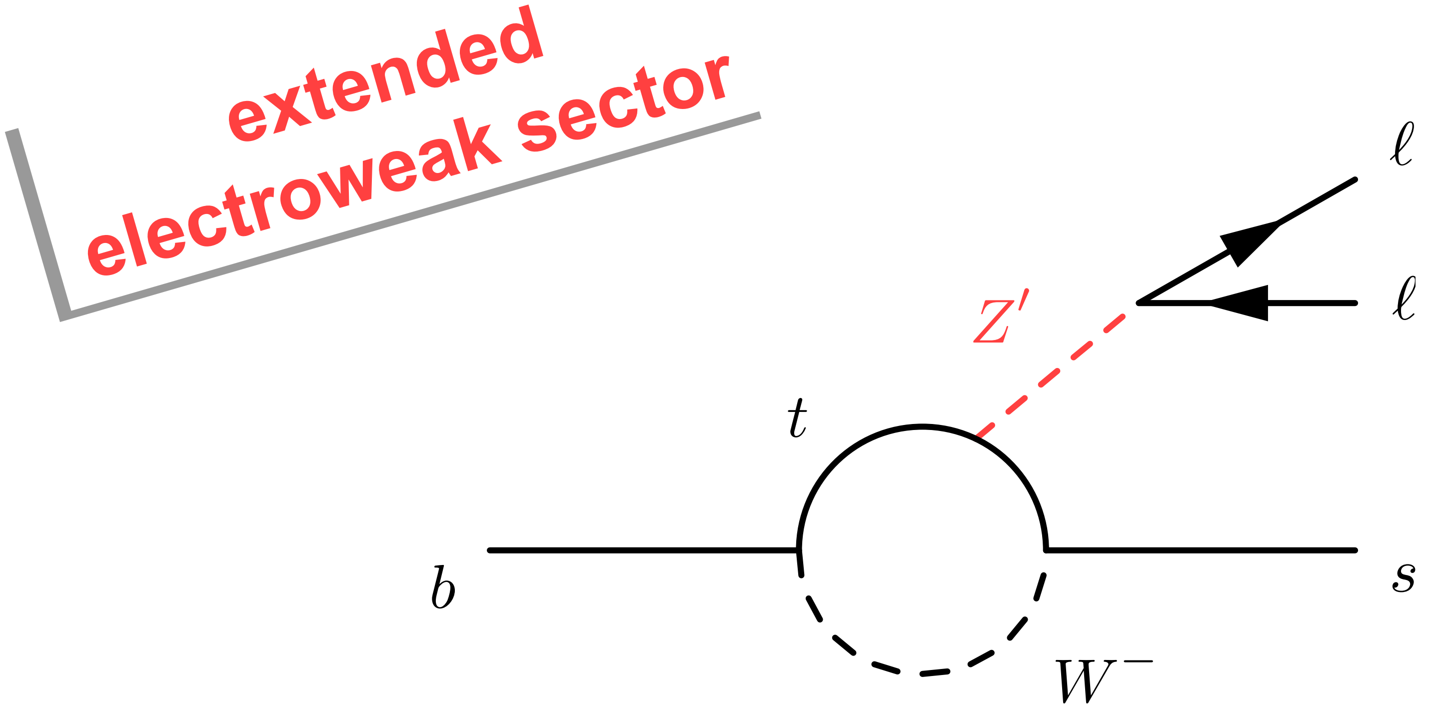
A hot topic

particle compositeness



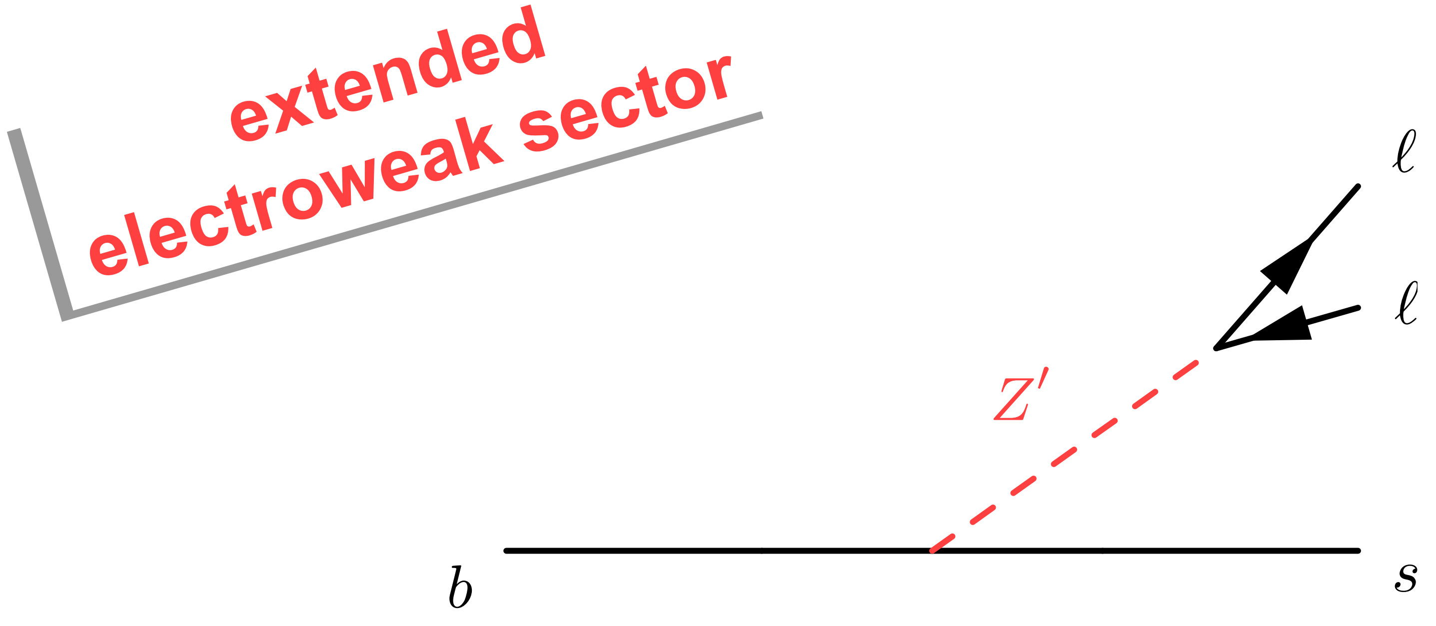
$b \to s\ell\ell$

A hot topic



$b \to s\ell\ell$

A hot topic

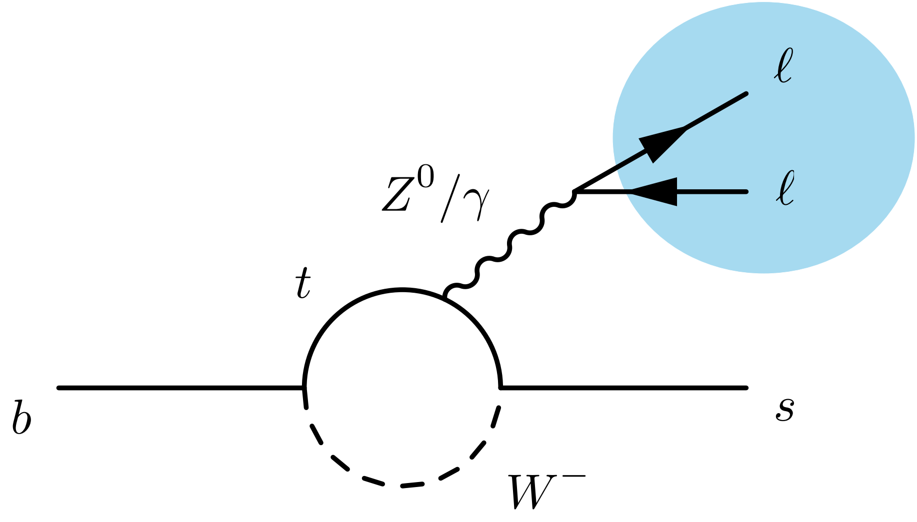


q^2

- Just before we get to the cool stuff, I need to introduce another piece of annoying jargon.
- It's kind of historical / stupid.
  - But everyone uses it.
  - And it's on a lot of xaxes for b-physics plots.
- The squared invariant mass of the pair of leptons.

$$q^2 = (p_{\mu^+} + p_{\mu^-})^\alpha (p_{\mu^+} + p_{\mu^-})_\alpha = m_{\mu\mu}^2$$

- You can think of it as like the internal energy share of the B decay products. Shared between the leptons and the quark bit.

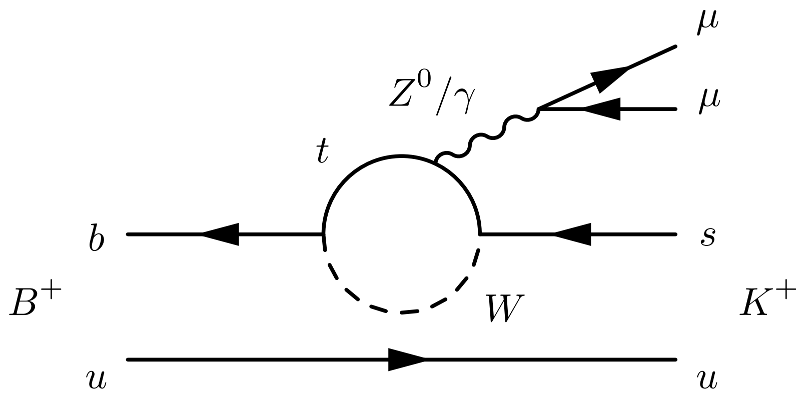


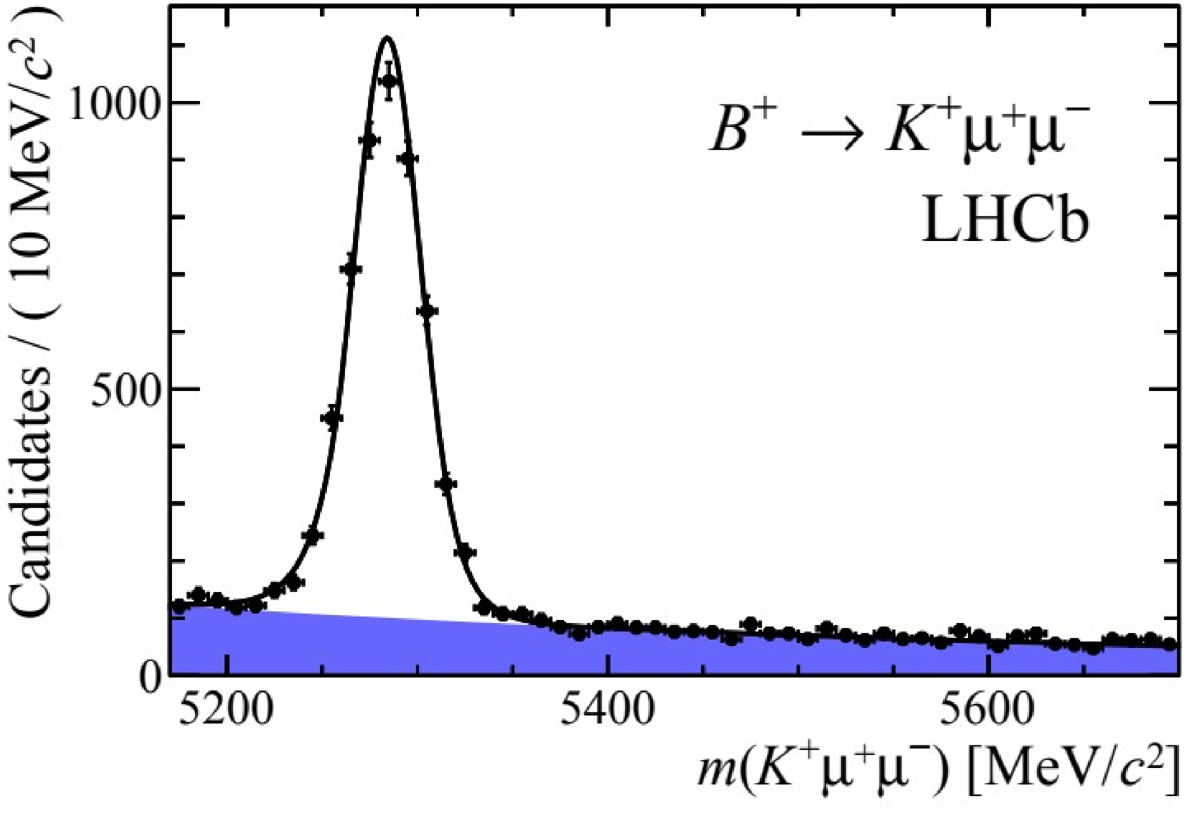
- Why don't we ever say "q" on it's own? Why not $m_{\mu\mu}^2$? …. I don't know.

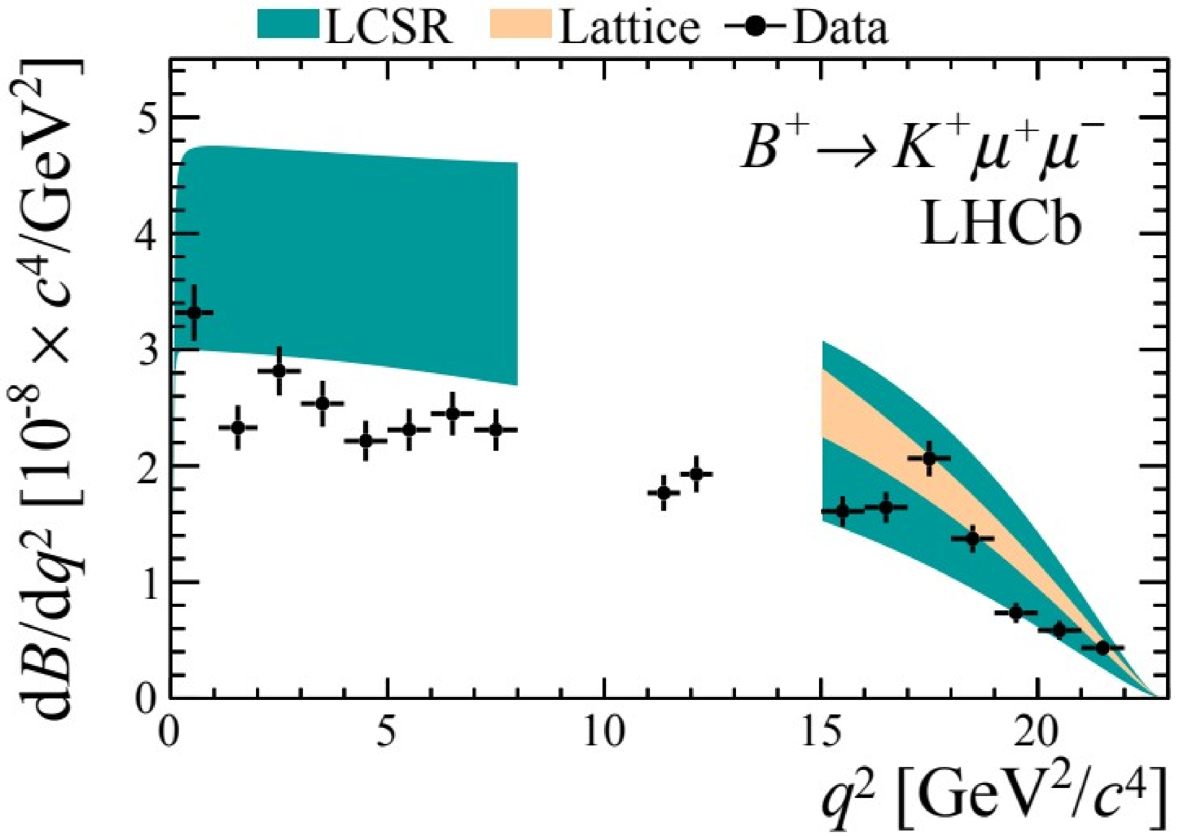
$B^+ \to K^+\mu^+\mu^-$

JHEP06(2014)133

- Take the $b \to s\mu^+\mu^-$ diagram
- … add a spectator u…
- Make invariant mass ($m_{K\mu\mu}$) plot,
- Fit to extract signal yield.
- Measurement is low wrt SM predictions at low q^2.



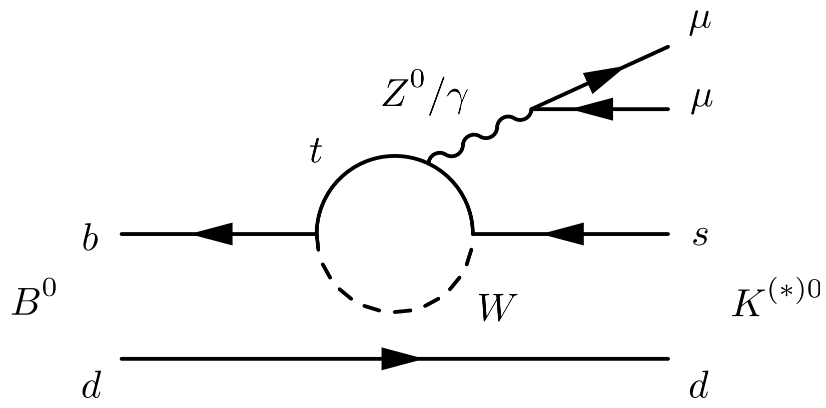


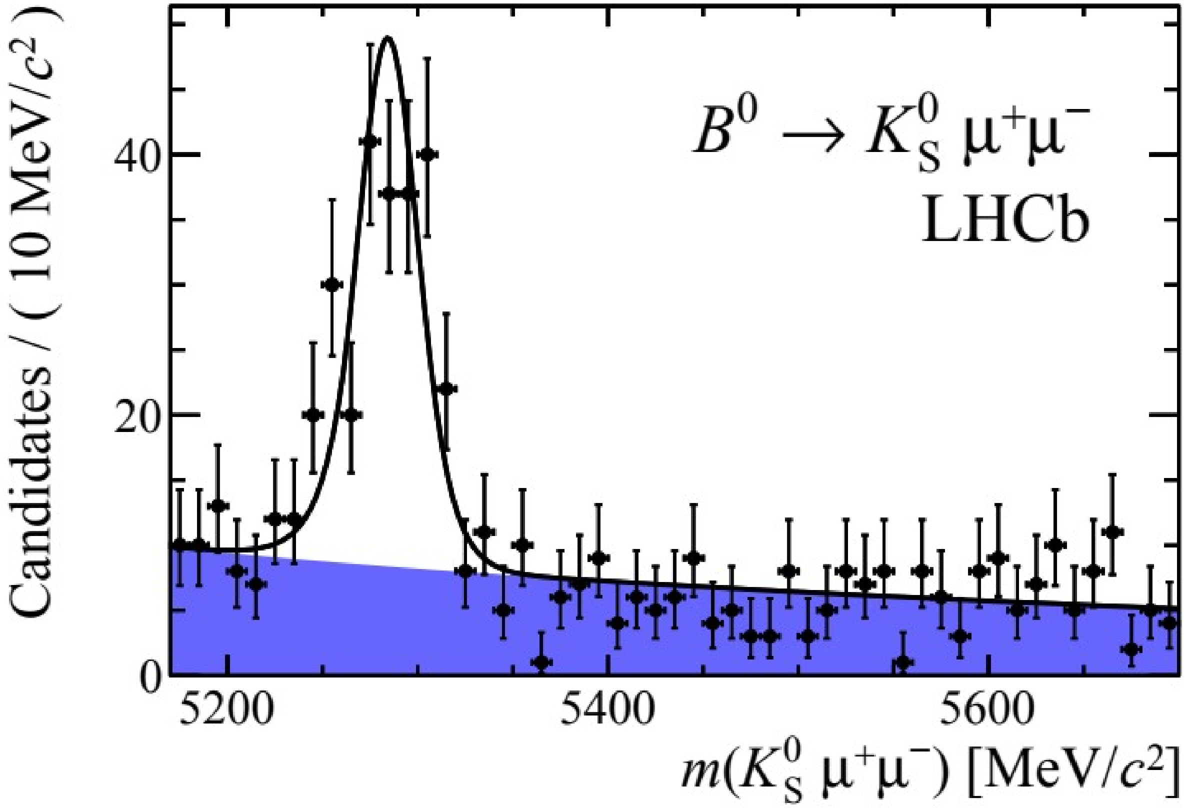


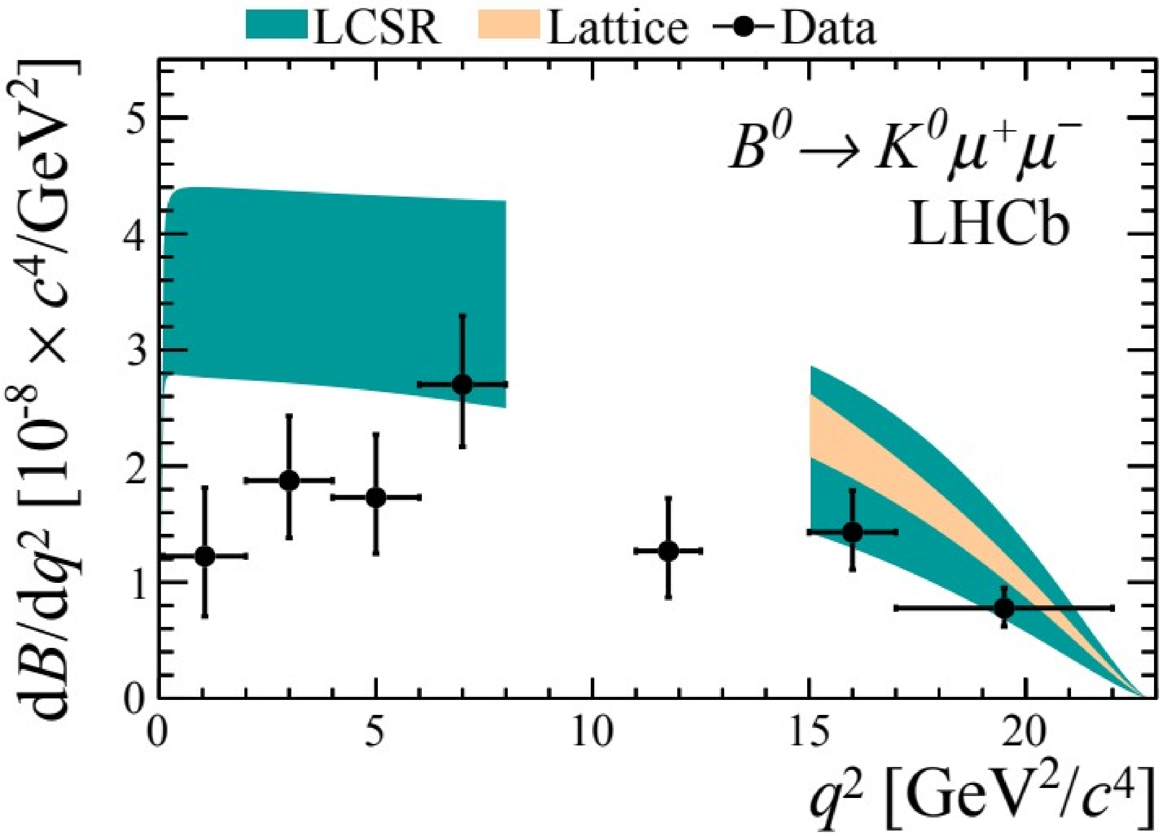
$B^0 \to K_S^0\mu^+\mu^-$

JHEP06(2014)133

- Take the $b \to s\mu^+\mu^-$ diagram
- … add a spectator d…
- Make invariant mass ($m_{\pi\pi\mu\mu}$) plot,
- Fit to extract signal yield.
- Measurement is low wrt SM predictions at low q^2.



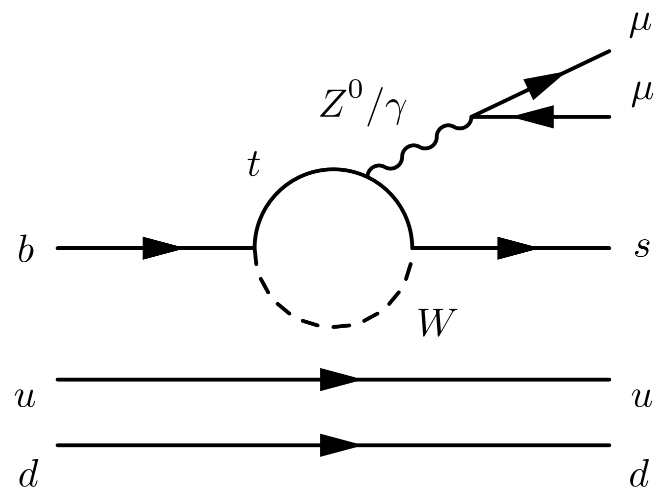


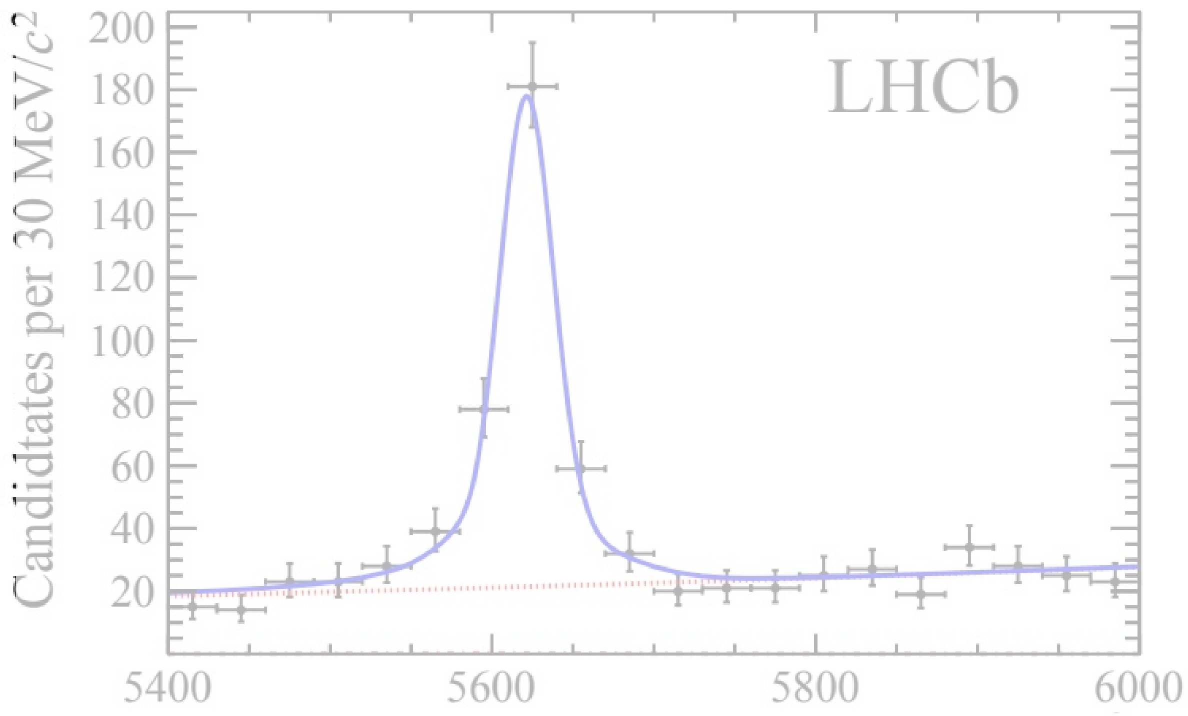


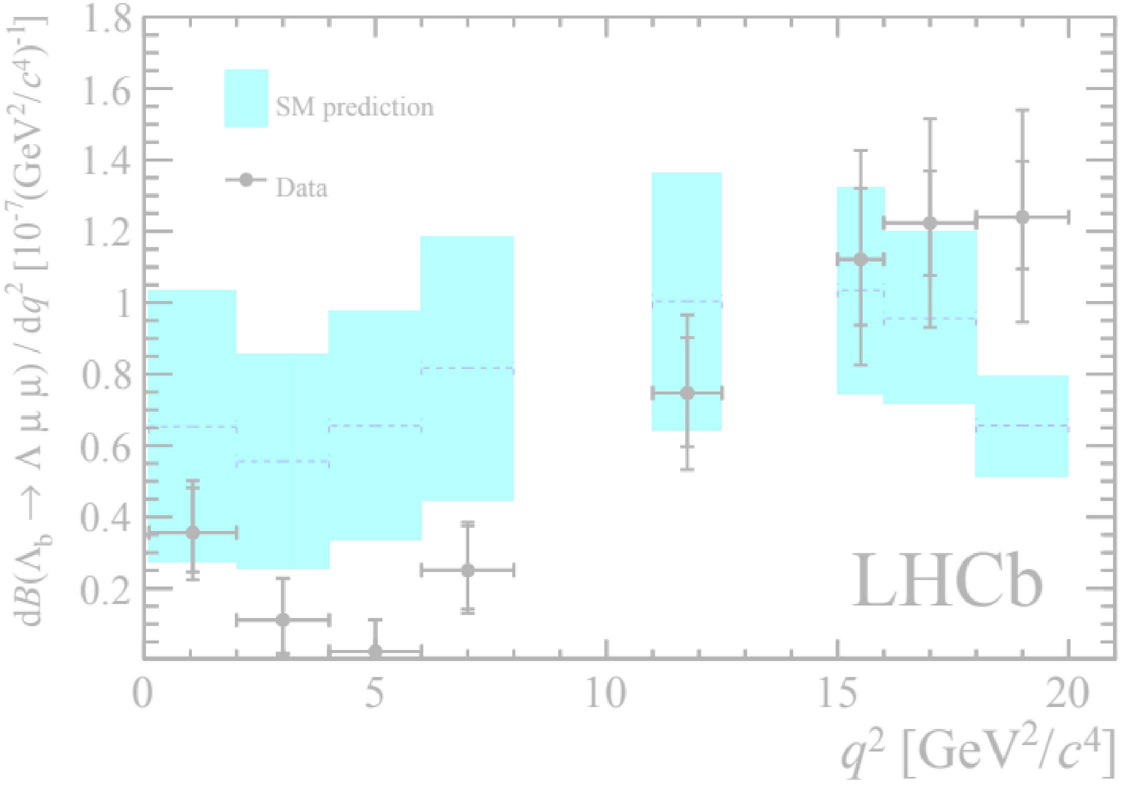
?→?μ⁺μ⁻

JHEP06(2015)115

- Take the b → sμ⁺μ⁻ diagram
- … add **two** spectators and flip the b quark direction …
- Make invariant mass ($m_{p\pi\mu\mu}$) plot,
- Fit to extract signal yield.
- Measurement is low wrt SM predictions at low q².



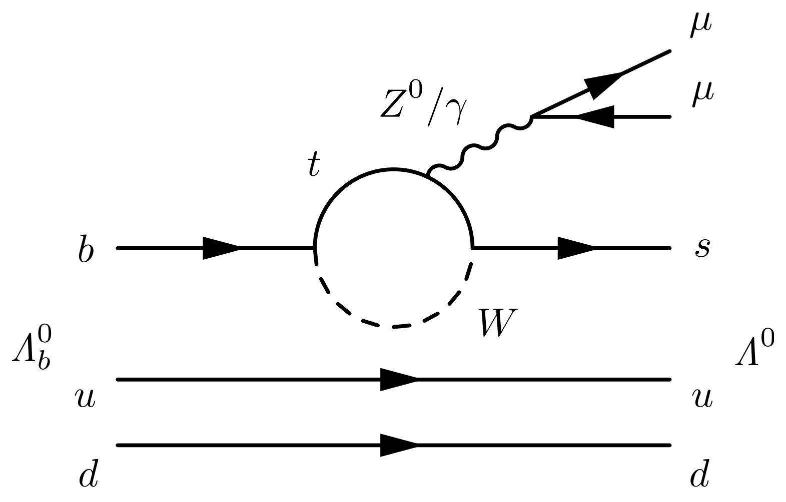


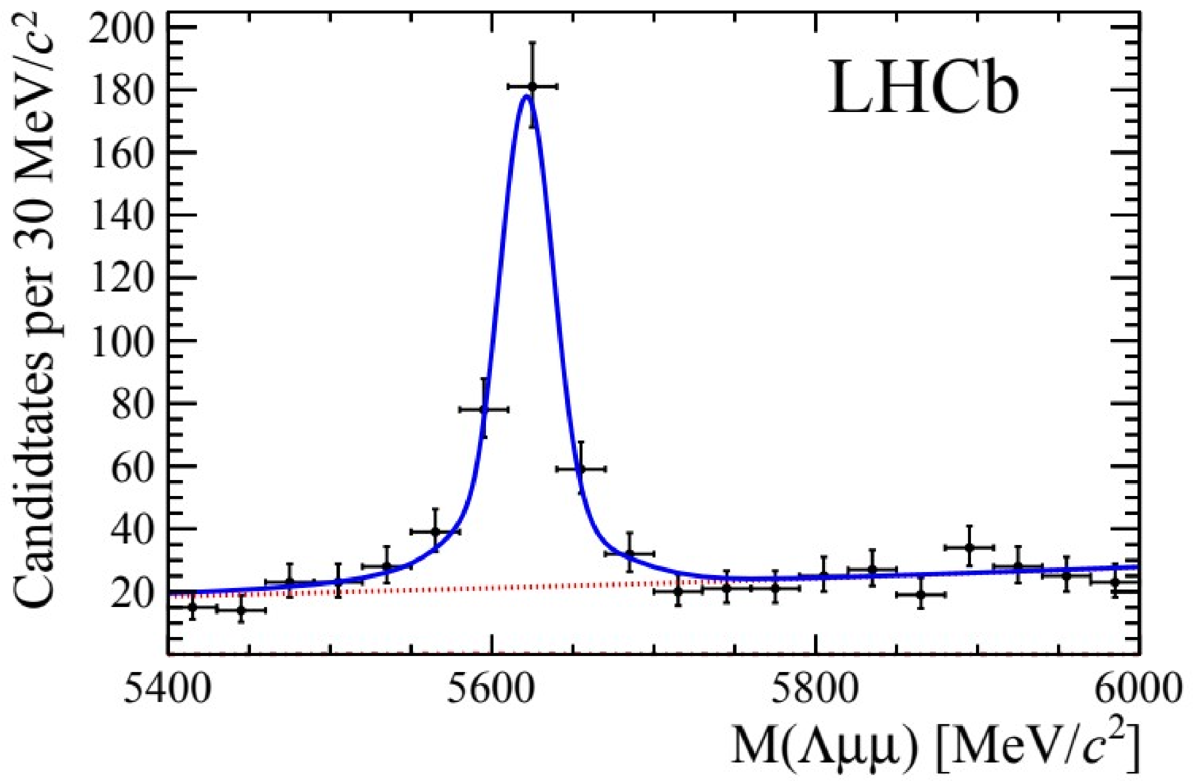


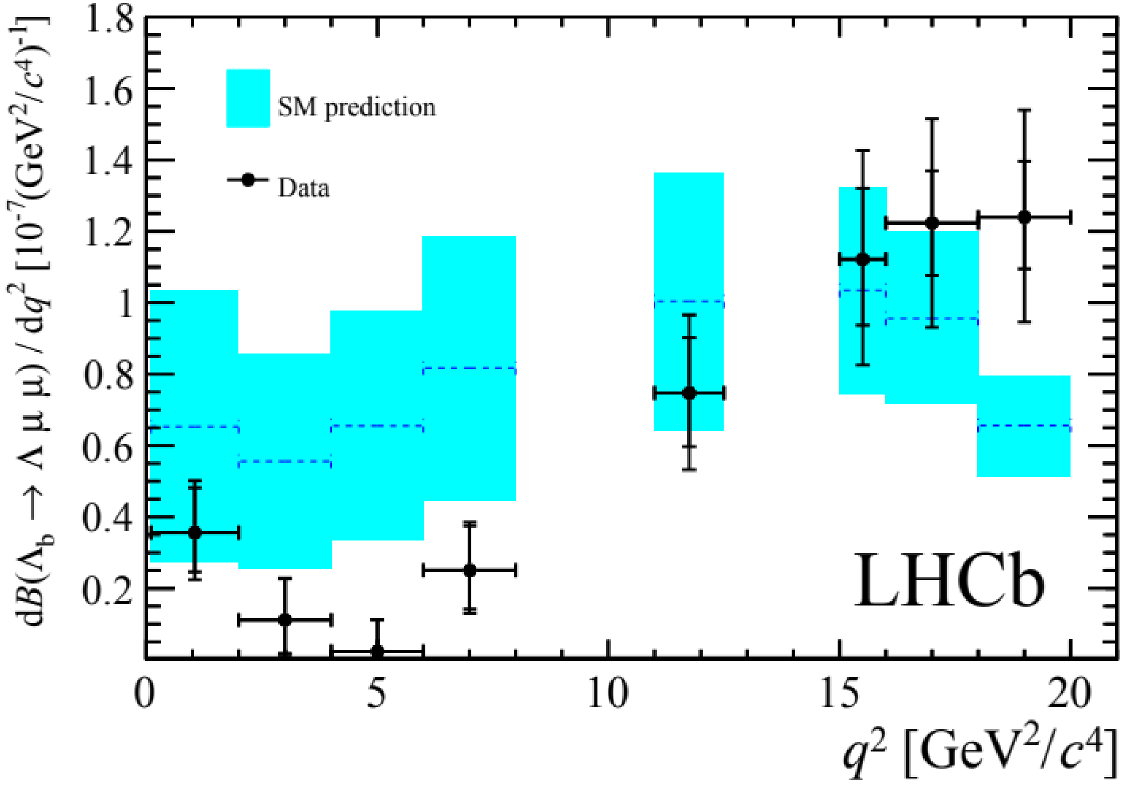
$\Lambda_b^0 \to \Lambda^0 \mu^+ \mu^-$

JHEP06(2015)115

- Take the $b \to s\mu^+\mu^-$ diagram
- … add **two** spectators and flip the b quark direction …
- Make invariant mass ($m_{p\pi\mu\mu}$) plot,
- Fit to extract signal yield.
- Measurement is low wrt SM predictions at low q^2.



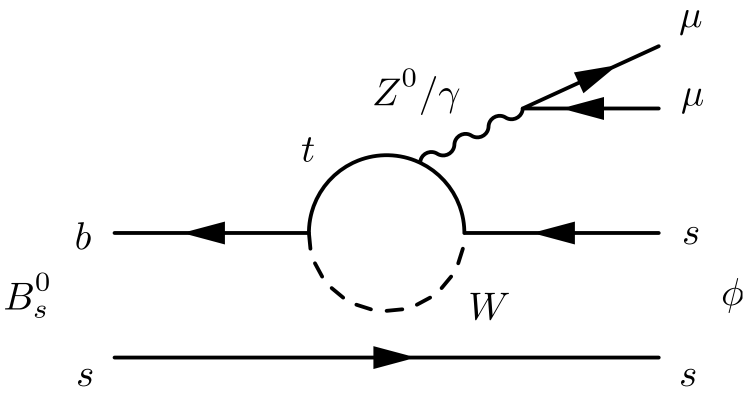


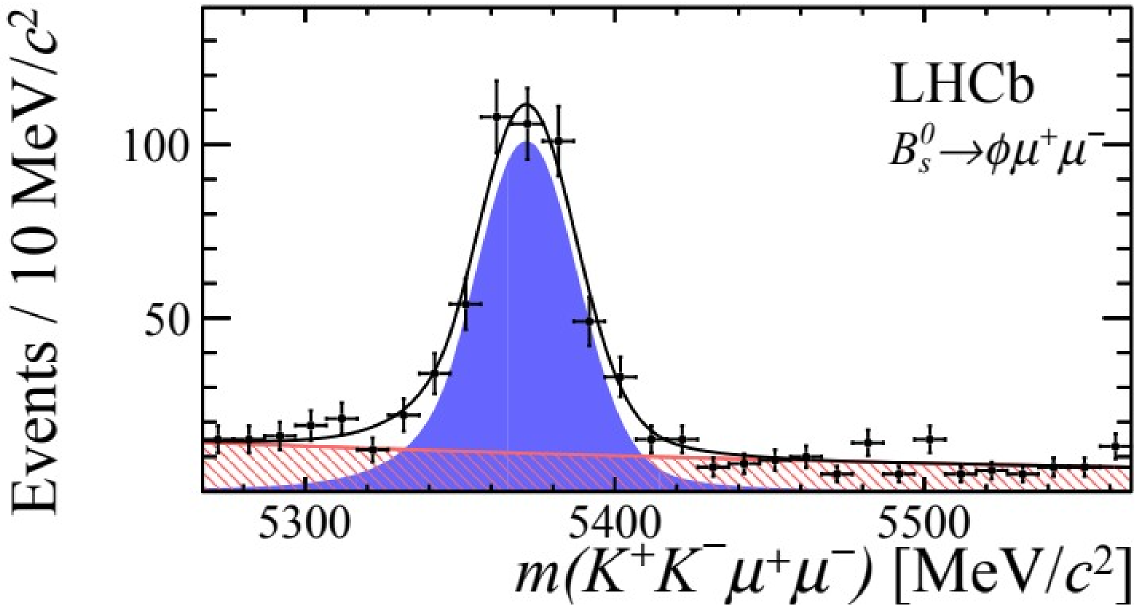


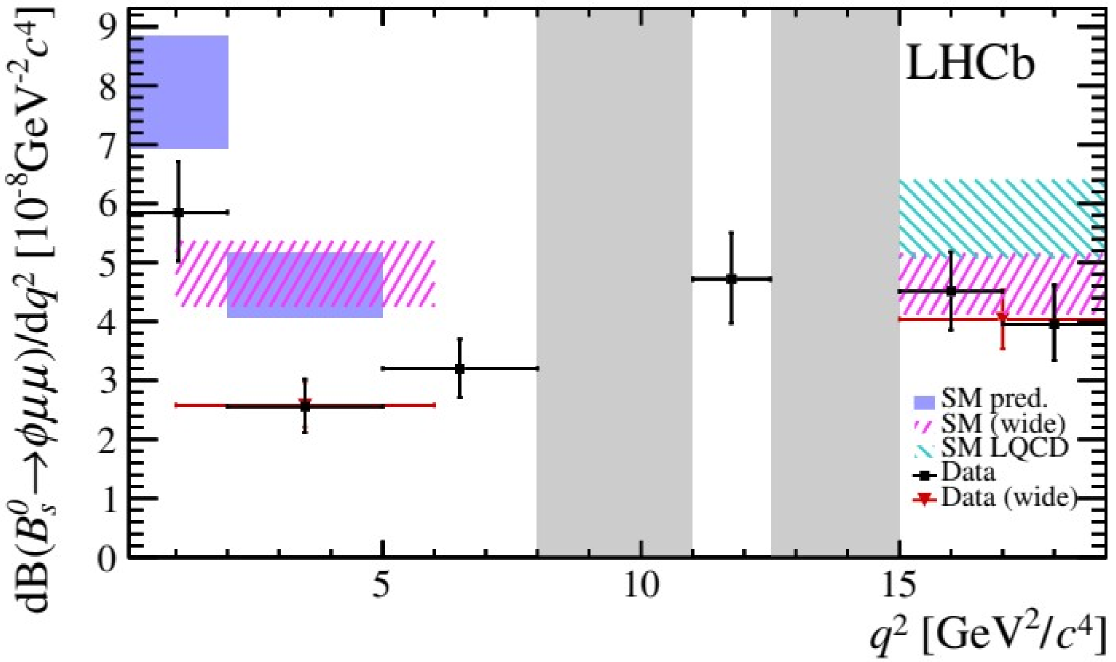
$B_s \rightarrow \varphi^0\mu^+\mu^-$

JHEP09(2015)179

- Take the $b \rightarrow s\mu^+\mu^-$ diagram
- … add a spectator s…
- Make invariant mass ($m_{KK\mu\mu}$) plot,
- Fit to extract signal yield.
- Measurement is low wrt SM predictions at low q^2.

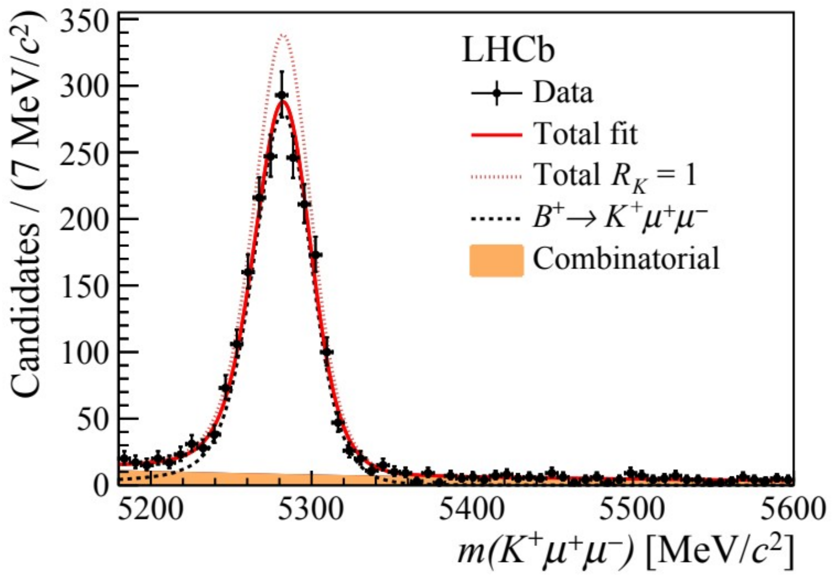


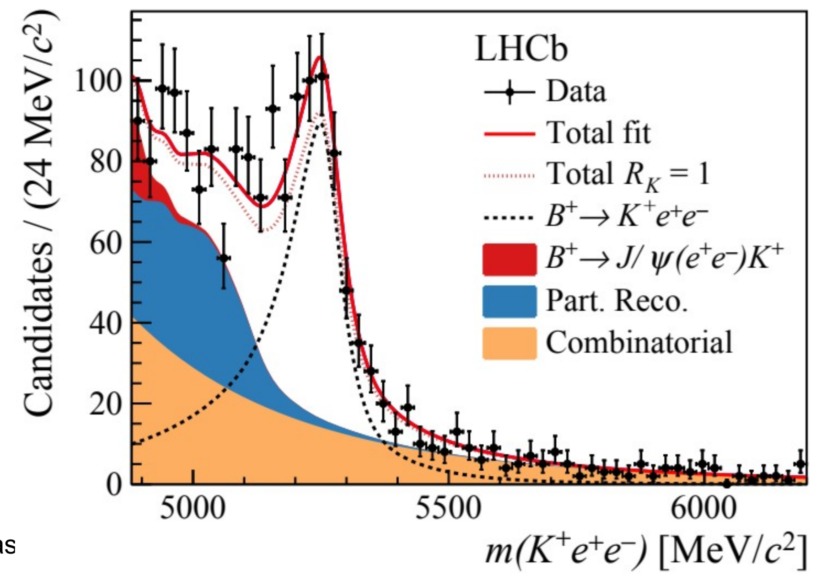




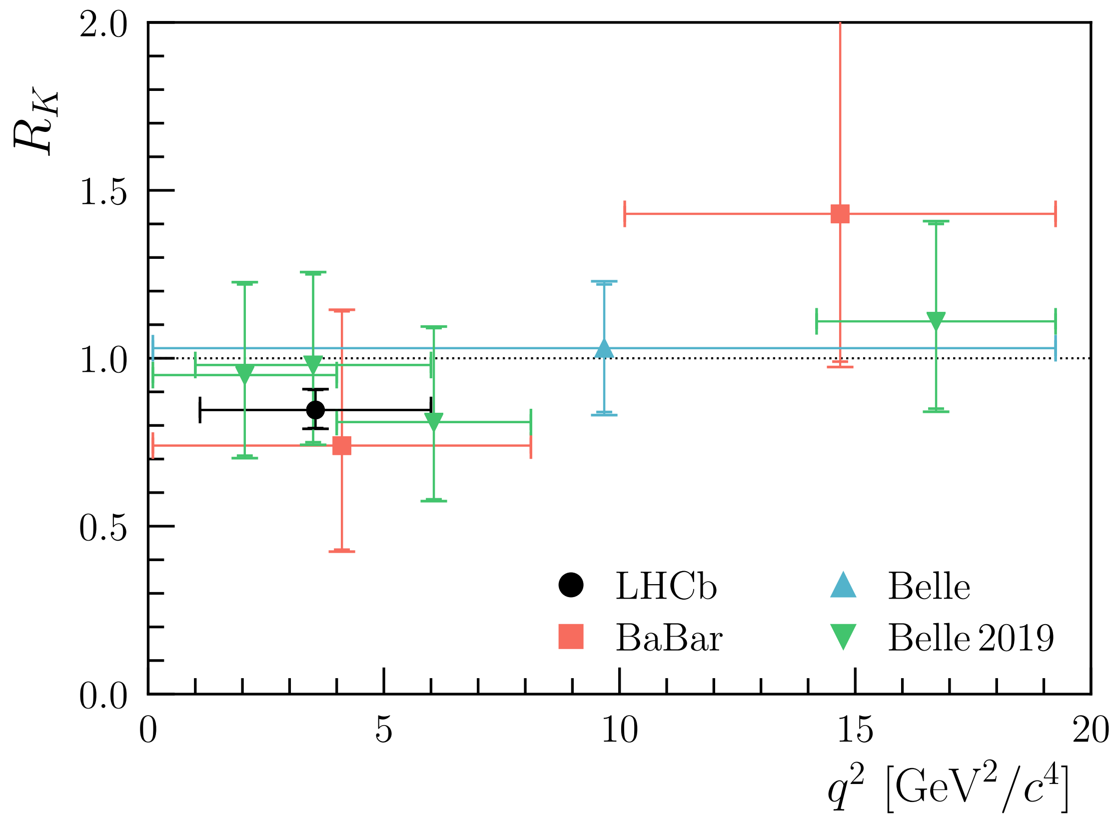
$R_K = \mathcal{B}[B^+ \to K^+\mu^+\mu^-] / \mathcal{B}[B^+ \to K^+e^+e^-]$

PhysRevLett.122.191801





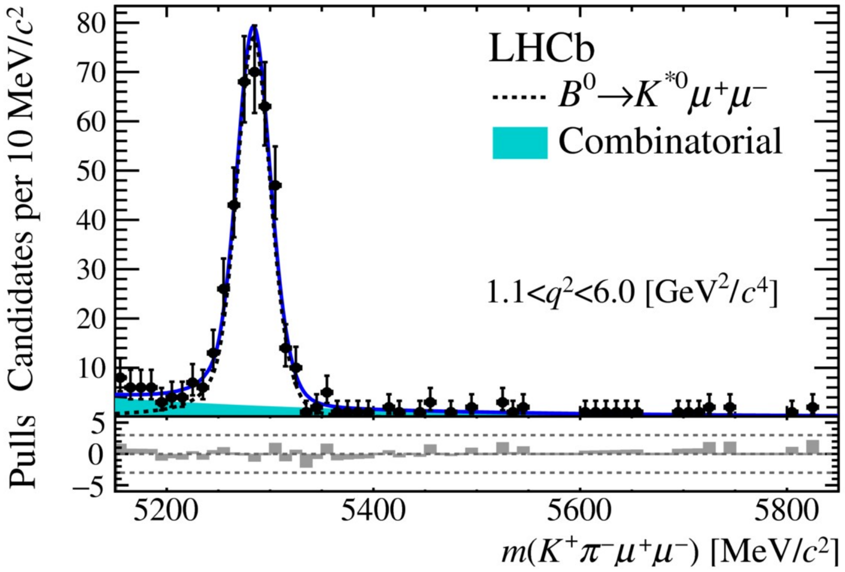
- Remember why ratios are a good idea?
- Look at the x labels of the histograms, which is which mode?
- The SM predicts R_K = 1.000.
- LHCb observes **0.846 ± 0.07**.

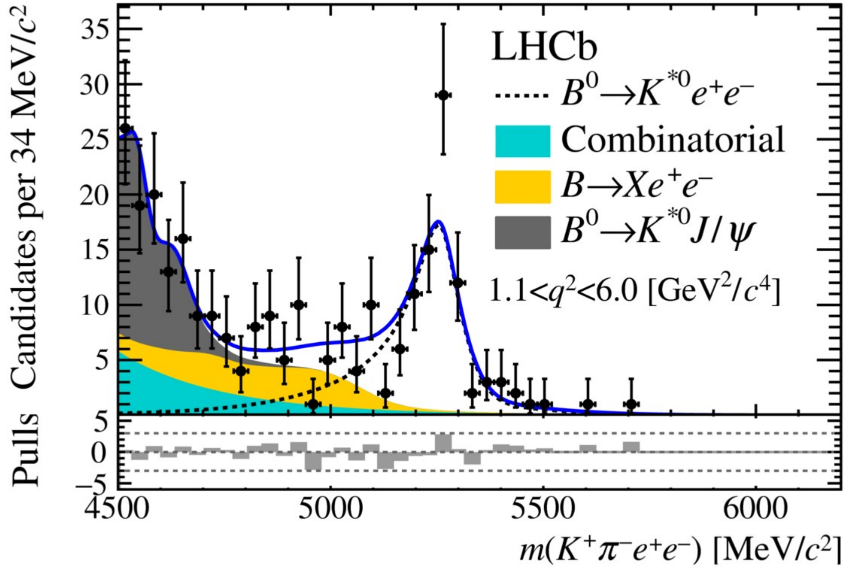


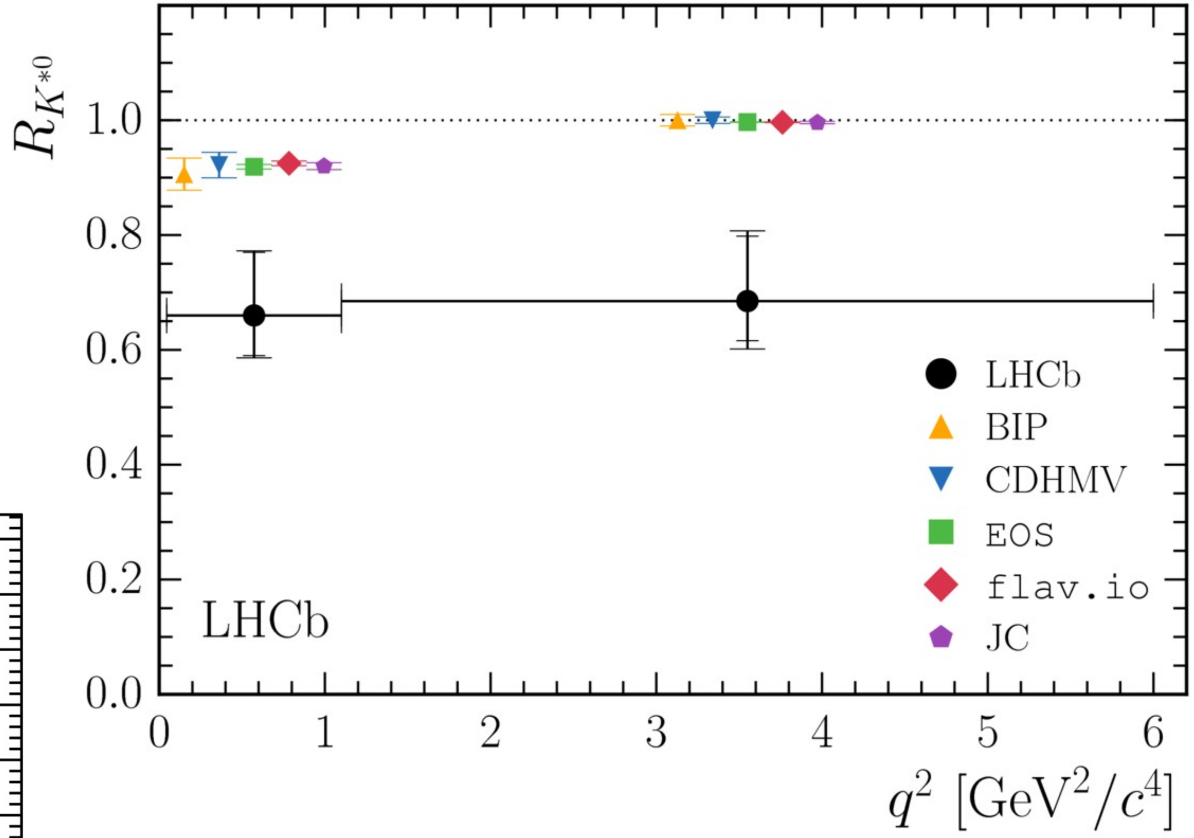
$R_{K^*} = \mathcal{B}[B^0 \to K^{*0}\mu^+\mu^-] \,/\, \mathcal{B}[B^0 \to K^{*0}e^+e^-]$

JHEP08(2017)055

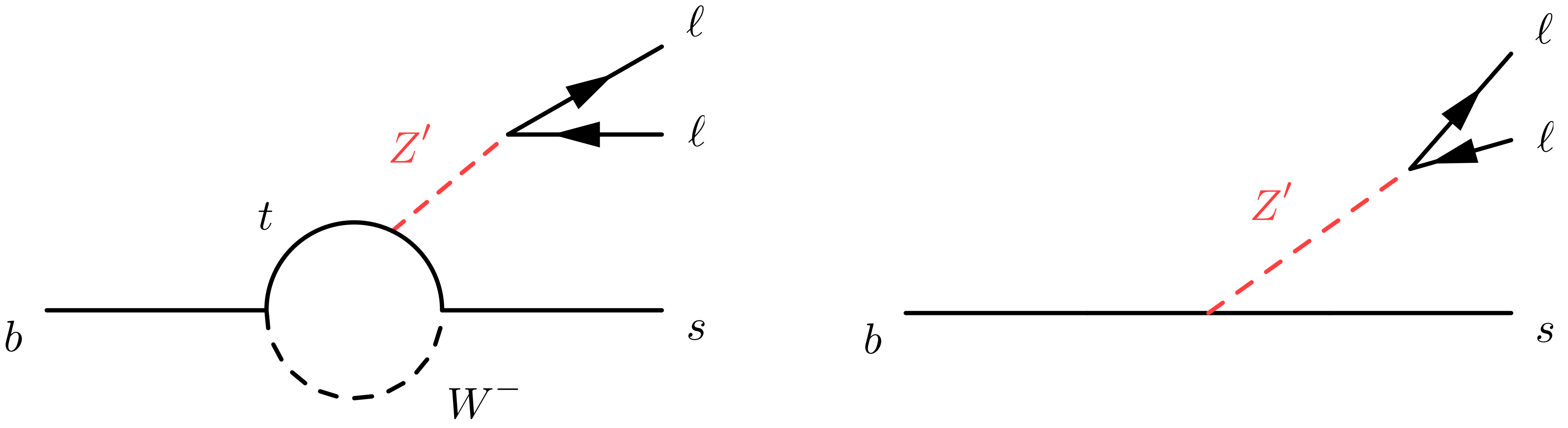
- Same story.







Is this the way the hints are pointing us?



0. What?
1. Experiments
1. Observables
2. Rare decays and anomalies
2. The field in 202X

… in summary

Only *somewhat* impartial overview

- Flavour physics is interesting !
  Despite our problem with stupid nomenclature.
- We study the transitions between cells in “the table”.
- We divide, sum, take the difference, of observable quantities.
  … Like branching fractions.
- There are two main active b-physics experiments now:
  - Belle II is taking data (despite pandemics).
  - LHCb is upgrading the detector.
- I hope you consider a PhD in this (sub)field.
- If you don’t, at least be friends with us! Now you know a bit of the lingo.

How did I do?

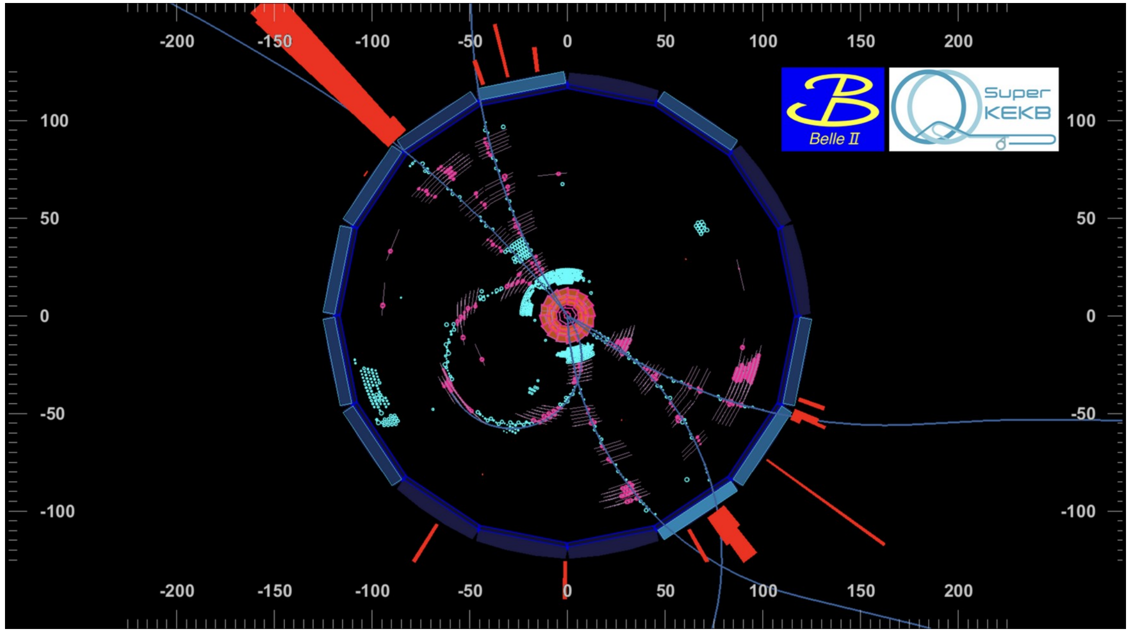
0) What is flavour and "flavour physics".

1) Understand the basics and motivations of flavour physics
   - Enough to talk to us even if you don't end up working in our field.
   - Know the names and rough idea behind four of the important b-physics experiments.
   - Know enough to "get the gist" of a flavour physics paper.

2) Know a bit about "recent anomalies" and their implications
   - Real cutting-edge physics results.

What next?

- This was quite a "full-on" lecture. Sorry about that.
- I will be online in the slack chat for the rest of the day. I made a **#flavour** channel.
- ...and you can email me! sam.cunliffe@desy.de
- There are some "fun" homework problems attached to the [agenda page]() (maybe Olaf will collect all of the homework Q's & A's somewhere).



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